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The following report from the Science Definition Team (SDT) describes their science recommendations for the proposed Jupiter Icy Moons Orbiter (JIMO) mission. The SDT was chartered by NASA in February 2003 immediately after the JIMO mission was announced. The primary responsibility of the SDT has been to provide guidance to NASA that can be used to optimize the scientific return from the JIMO mission within programmatic constraints. The SDT was also charged with ensuring that this guidance reflects the current state of understanding of the Jupiter system and the needs of the science community.

The SDT met these responsibilities by composing a prioritized set of science objectives, investigations, and measurements for the mission. In addition, the SDT and the JIMO Project Office at the Jet Propulsion Laboratory worked closely together to begin deriving the requirements necessary to ensure that the spacecraft and mission design can accomplish these recommendations.

The Jupiter Icy Moons Orbiter is one of the most ambitious robotic missions NASA has ever undertaken. NASA recognizes input from the scientific community is the vital first step in the program's success. I would like to thank the SDT for their hard work over the past year, and appreciate the ambitious expectations they have set forward for the mission.

I look forward to the continued participation of the science community as a whole and the SDT in particular as the Outer Planets Program and JIMO continue.

Sincerely,

Orlando Figueroa
Division Director for Solar System Exploration

Report of the

NASA SCIENCE DEFINITION TEAM

for the

JUPITER ICY MOONS ORBITER (JIMO)

Dr. Ronald Greeley, SDT co-chair
Arizona State University

Dr. Torrence Johnson, SDT co-chair
Jet Propulsion Laboratory

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Report of the NASA *Science Definition Team* for the *Jupiter Icy Moons Orbiter*

Executive Summary

The *Jupiter Icy Moons Orbiter* (JIMO) affords an exciting and unprecedented opportunity to explore a part of the solar system identified by the *National Academy of Sciences* as critical in the search for life's origins and the understanding of planetary evolution. The *Science Definition Team* (SDT, Appendix 1) for JIMO consisted of 38 scientists representing the community interested in the exploration of the Jupiter system, with a focus on *Europa, Ganymede,* and *Callisto*. The SDT was appointed by NASA in February 2003 to derive the scientific objectives for the JIMO mission. Early in the process, the SDT determined that the approach to the study should include the following guidelines:

- The JIMO mission represents a substantial investment in time, intellect, and other resources; therefore there must be a commensurate high scientific return from the project,
- Formulation of the scientific objectives should include solicitation of ideas from the entire planetary community,
- There should be close interactions with JIMO Project engineers to ensure their understanding of the scientific requirements for the mission and that the SDT understand the engineering feasibility of those requirements.

The scientific foundations for the JIMO mission include recommendations from previous studies by the *National Research Council* (NRC, 1999, 2003) and *NASA* (2003), which identify Europa and the Jupiter system as high priority objects for solar system exploration and the search for life's origin. In addition to these documents, input to the SDT was obtained from a community-wide meeting entitled "Forum on Concepts and Approaches for the Jupiter Icy Moons Orbiter," *LPI* (2003). After a series of presentations, the ~150 participants at the *Forum* were organized into seven groups by scientific discipline to identify the high priority issues that could be addressed by the JIMO mission. The results from the seven groups served as the basis for subsequent SDT deliberations.

The goals presented in this document, and their detailed objectives and investigations, were derived by scientific specialization. The SDT synthesized the various investigations to derive an over-arching statement for the JIMO mission:

> ***Explore the icy moons of Jupiter and determine their habitability in the context of the Jupiter system***

which includes three *crosscutting themes:* ***Oceans*** (finding their locations, studying the structure of their icy crusts, and assessing active internal processes), ***Astrobiology*** (determining the types of volatiles and organics on and near the surfaces, and the processes involved in their formation and modification), and ***Jovian System Interactions*** (studying the atmospheres of Jupiter and the satellites and the interactions among Jupiter, its magnetosphere, and the surfaces and interiors of the satellites).

The SDT has formulated four equally important goals for the JIMO mission. Within each goal, the objectives, investigations and measurements have been identified and prioritized. The goals are summarized as follow:

- **SURFACE GEOLOGY AND GEOCHEMISTRY GOAL: to determine the evolution and present state of the Galilean satellite surfaces and subsurfaces, and the processes affecting them.**

JIMO near-global high resolution imaging in the visible and infrared, with corresponding topographic mapping and subsurface sounding, will enable the determination of the styles, distribution, and importance of active processes that have shaped the icy satellites' surfaces over time. This information will provide further insight into why the evolutionary path of each moon is different. These measurements will enable the determination of the places and processes by which Europa's putative ocean might communicate with the surface, and how erosional processes operate. In addition, high resolution mapping of selected areas will enable the identification of sites that are the most promising candidates for exploration on the surface. Remote sensing observations of Io will provide insight into geologic and magnetospheric processes, heat flow, and exchange of material among all of the satellites.

- **INTERIOR SCIENCE GOAL: to determine the interior structures of the icy satellites in relation to the formation and history of the Jupiter system, and the potential "habitability" of the moons.**

The primary objective in meeting this goal is to determine the presence and location of liquid water beneath the moons' icy crusts. This will involve understanding the extent of the satellites' differentiation, establishing whether they contain subsurface oceans, characterizing and mapping the location of possible water and brines, and measuring the thickness of the ice overlying any putative oceans. Geophysical methods (gravity, altimetry, magnetic field) are the primary means of making a global estimate of ice thickness. These techniques will be greatly enhanced by making seismic measurements on the surface. A secondary objective is to assess the active processes that have caused the moons to evolve internally. This objective involves searching for evidence of current and past internal activity, as reflected by gravitational and magnetic fields, topographic and subsurface changes, and evidence of thermal anomalies. A tertiary objective is to understand the formation and evolution of the Jupiter system by investigating the composition of Jupiter's deep atmosphere, and by placing bounds on the orbital evolution of the satellites by studying the orbital and rotational dynamics of all four large satellites, including measuring the rate at which Io dissipates tidal energy in the form of heat.

- **ASTROBIOLOGY GOAL: to search for signs of past and present life and to characterize the habitability of the Jovian moons with emphasis on Europa.**

The JIMO mission provides a unique opportunity to seek evidence of biotic or prebiotic activity in an extraterrestrial environment. Liquid water is essential for all known living systems and the icy satellites may contain some of the largest reservoirs in our solar system. Whether or not icy satellites have ever provided an abode for biotic or prebiotic activity has important implications for understanding the origin of life. The detection of signs of past or present life will require measurements of certain biogenic organics with specific biological patterns and chirality or specific biomarkers known to be relevant to life. Life forms also cause isotopic fractionation of atoms that constitute biomass. In addition, life generally leads to chemical disequilibrium in the environment and, thus, *in situ* or remote sensing of metabolic byproducts can help detect signs of life. To evaluate habitability it is important to determine the presence of liquid water, the concentration of major biologically relevant ions as sources of energy and nutrients, and the potential effects of radiation on life forms.

- **JUPITER SYSTEM SCIENCE GOAL: to determine how the components of the Jovian system operate and interact, leading to the diverse and possibly habitable environments of the icy moons.**

The planet, satellites, rings, dust, gas, particles and fields in the Jupiter system influence each other through many complex interactions. Understanding these interactions provide insight into the characteristics of other bodies in the Solar System. Measuring Jupiter's elemental abundance ratios will help determine the nature, history, and distribution of volatile and organic compounds in the Solar System. Understanding of the dynamics of Jupiter's atmosphere and magnetic field provide insight into the deeper structure of Jupiter.

The icy moons interact with Jupiter's magnetosphere through charged particle bombardment, which modifies their surface chemistry, produces tenuous atmospheres and ionospheres, and leads to rings of gas and dust circling Jupiter. These processes are generally harmful to life, but they could also be a major source of energy for possible biota in the oceans of the icy moons. Finally, observations of the charged particle bombardment on the chemistry of the environment is important to studying their habitability. Measurements from JIMO on the electromagnetic induction responses from the moons to Jupiter's rotating field will reveal information about the interiors of the moons, including the presence of liquid sub-ice oceans.

Based on the prioritizations within the four goals outlined above, the SDT has formulated a set of science *baseline investigations and measurements* and *science floor investigations and measurements.* The *science floor* is defined as the minimum science the JIMO mission must accomplish in order to be viable from a scientific standpoint, while the *baseline* represents the ideal JIMO mission the SDT believes should be undertaken. These are summarized in Table 1.1.

A critical element of the baseline mission is a small surface package for Europa, termed the *Europa Surface Science Package* (ESSP). Many high-priority measurements can be made only from the surface of Europa. The SDT crafted these high-priority measurements for a landed package within the framework of the objectives and investigations for the overall mission and are grouped into three science areas: 1) *Astrobiology*, in which measurements of organic materials, inorganics (e.g., oxidants) relating to survival and recognizability of biochemical signatures of life, and searches for patterns indicative of biology must be made *in situ*, 2) *Geophysics*, in which acoustic/seismic measurements made from the surface enable constraints to be placed on the interpretations of data taken from orbit regarding the presence of liquid water and the structure of the icy crust, and 3) *Geology-geochemistry* in which *in situ* measurements of other inorganic chemical species (e.g., sulfate hydrates) at the surface provide ground truth for remote sensing data and insight into the structure of the surface at sub-meter scales and the possibility of chemical exchange between the surface and a sub-surface ocean. Astrobiology and geophysical measurements are of highest priority; while geology-chemistry measurements not

Table 1.1 Science Floor and Baseline Investigations for the Jupiter Icy Moon Orbiter.

	Goals and Objectives											
	SURFACE GEOLOGY AND GEOCHEMISTRY		INTERIOR SCIENCE			ASTROBIOLOGY		JUPITER SYSTEM				
Investigations	Geological history, mechanisms	Comp. Evolution	Location of water	Evolution of internal structure	Form evol. Jupiter system	Signs of life	Habitability	Interactions	Jupiter atm.	Magneto-sphere	Io interactions	Ring system
Science Floor												
Magmatic and tectonic processes on Galilean satellites	x	o	x	x			x	o			o	
Europa surface-subsurface material interchange	x		x	x			x					
Surface ages and subsurface structure via cratering	x	o	x	x			x	o				
Evidence of recent surface activity	x	x	o	o	o		o					
Surface age from erosion/deposition and energy/matter flux	x	o	o	x								
Identification & distribution of surface components	o	x		o				o			o	
Europa global heat flow	o	x										
Extent of differentiation of the icy satellites			x	x	o		x					
Presence of sub-ice oceans	o		x	o	o		x					
Distribution of possible liquid beneath crusts	x	o	x	x	o		x					
Thickness of ice layer	x	o	x	x	o		x					
Evidence for current internal activity	o	o	o	x	o		o				o	
Evidence for internal activity on geologic time scales	x	o	x	x	o		x					
Biogenic organics at Europa's surface and shallow subsurface						x						
Effects of magnetosphere on icy moons								x		x		
Interior structure of icy moons from electromagnetic induction								x		x		
Jupiter atmospheric dynamics									x			
Structure of Jovian magnetosphere										x		
Magnetospheric coupling of satellites and Jupiter										x		
Baseline												
Europa high-res surface properties	o	o	o	o								
Surface chemistry processes		o						o				
Io regional/global heat flow	o	o			o							
Temperature-dependent stability of surface components	o	o	o	o								
Place bounds on orbital evolution of the moons	o	o			o							
Sizes/states of the cores of the moons	o		o	o	o		o					
Iotopic fractionation in organic/inorganic compounds						o						
Presence of potential metobolic by-products						o						
Nature/distribution of abiotic organic matter		o				o		o				
Search for organisms by microscopy						o						
Composition of surface and shallow subsurface ice on Europa							o					
Environmental resources of energy							o					
Radiation effects on stability of organic molecules							o					
Effects of particle sputtering on moons' surface/atmosphere		o						o				
Temperature and energy balance of Jupiter									o			
Jupiter's clouds, hazes, and precipitation									o			
Composition of Io's atmosphere		o									o	
Relationship of Io volcanic activity to torus and aurorae											o	
Particle size distribution in each ring component												o
3-D structure of ring system												o
Composition of rings and embedded moons		o										o
Small inner moon search												o

x = Science floor (minimum needed for a viable mission)
o = Baseline

directly related to the search for biochemical signatures are of lower priority but should be done to determine composition of the non-ice materials thought to be sulfate hydrates and possibly originating from the ocean. Data from the *Galileo* mission are sufficient to identify sites of scientific interest for the ESSP. The SDT recommends that the final selection of a site be a community-wide activity.

The overwhelming consensus of the SDT is that, given the high scientific potential from a landed package and the large resources that would be committed to the JIMO mission, a surface package to Europa should be included. Moreover, the SDT considers that up to ~25% of the science resources, in particular, mass, could be devoted to the ESSP. However, in recognition of the potential implementation uncertainty, the SDT has placed the ESSP in the baseline mission, but not in the science floor. A study of the feasibility of the ESSP should be made, and the SDT would assess the scientific trades in response to the study.

The SDT recognizes that the revolutionary nature of the JIMO spacecraft will require significant technology development time before a payload is competitively selected. In order to provide science requirements during that development, the SDT has worked closely with the JIMO Project to derive the *Payload Accommodation Envelope* (PAE). The PAE is a set of spacecraft requirements needed to accomplish the recommended science of the JIMO mission. A particularly important element is the ability to change the trajectory of the spacecraft repeatedly to orbit the icy moons individually. The SDT urges NASA to continue working with the SDT to refine the PAE until such time that instruments teams are selected and can work directly with the JIMO Project.

Based on previous studies by the National Academy of Sciences and NASA, results from the community "Forum," and discussions within the JIMO Science Definition Team, the SDT recommends that:

1. ***JIMO be implemented to meet all science baseline and floor objectives, investigations and measurements elucidated in Section 3.***
2. ***The JIMO project incorporate the science requirements defined in the PAE early in the design of the spacecraft, including a Payload Accommodation Envelope mass allocation of 1500 kg for science, capability for precise orbit determination and spacecraft electromagnetic cleanliness.***
3. **A Europa Surface Science Package** ***be incorporated into the JIMO mission baseline design.***
4. ***All the science instruments be competitively selected and flown as Principal Investigator provided investigations.***
5. ***A planetary protection policy and implementation strategy be established for the exploration of icy satellites.***
6 ***NASA select Interdisciplinary Scientists at an early stage in the mission development.***
7. ***NASA consider a competitively selected augmentation to the science teams 2 to 4 years prior to operations at Jupiter.***
8. ***An Outer Planets Data Analysis program be established.***

9. ***A Fundamental Research program for the Outer Solar System be established.***

10. ***A JIMO Data Analysis Program be established***

11. ***The resources for science be identified for the full life cycle of the* JIMO *mission.***

12. ***The JIMO project implement a ground data system to convert raw spacecraft data into useful science data products that are validated and archived.***

The recommendations and details on scientific potential outlined in this report for the Jupiter Icy Moons Orbiter represent the deliberations of the JIMO *Science Definition Team*. Although some individuals of the 38-member team had different view points on some issues, the report reflects the general consensus of the SDT. Because the JIMO concepts will continue to evolve beyond the date of this report (February 2004), it is important that a dialog continue among NASA Headquarters, project personnel, and the scientific community. In this context, there is the potential for this report to be revised and augmented in the future.

1.0 INTRODUCTION

1.1 Overview of the Science Definition Team (SDT)

NASA, through the *Solar System Exploration Division* of the *Office of Space Science* and the *Project Prometheus Program*, has determined that a spacecraft will be launched to explore the icy Galilean satellites, the *Jupiter Icy Moons Orbiter* (JIMO)*,* with a launch date of no sooner than 2011. Under the direction of the Director of the Solar System Exploration Division, a *Science Definition Team (SDT)* was formed for this mission. Membership and affiliations of the SDT are provided in Appendix 1. Prof. Ronald Greeley of *Arizona State University* and Dr. Torrence Johnson of the *Jet Propulsion Laboratory* co-chaired the SDT. The purpose of the SDT was to define the:

- Scientific goals and objectives of the JIMO mission, building on the recommendations from the National Research Council *Solar System Exploration "Decadal" Survey* and the NASA *Solar System Exploration Division Roadmap*. Key references are: 1) *New Frontiers in the Solar System, An Integrated Exploration Strategy* (NRC, 2003), 2) *The Exploration of Europa, Reports of the National Research Council Space Studies Board* (NRC, 1999), and 3) *Solar System Exploration, Roadmap for the Office of Space Science* (NASA, 2003).

- Science requirements for investigations that are most likely to make high priority measurements from the JIMO platform, using the enhanced capabilities provided by a nuclear reactor and nuclear electric propulsion (NEP).

The initial SDT meeting was held on 10 March 2003. At this meeting, representatives from NASA Headquarters provided an overview of the JIMO mission concept, and the JPL JIMO Project team described the general spacecraft and mission characteristics. Seven science theme subgroups were formed from the SDT to evaluate priorities of representative science disciplines [SDT subgroup leaders are identified in brackets; members subsequently added to the SDT are indicated in italics]:

- Remote sensing: geology, geochemistry [L. Prockter, *P. Schenk*, D. Blaney, *J. Spencer*]
- Surface geophysics, geochemistry [N. Makris, *W. Moore*]
- Magnetospheres, satellite interactions, atmospheres, geophysics, geodesy [K. Khurana, *W. Kurth*]
- Global, interior structure [D. Stevenson, *W. McKinnon*]
- Subsurface [D. Blankenship, *D. Winebrenner*]
- Atmospheric science [A. Ingersoll, *A. Simon-Miller*]
- Astrobiology [C. McKay, *D. Warmflash*]

These subgroups addressed specific issues in subsequent telecons, email exchanges, and meetings.

The second meeting of the full SDT was held in conjunction with the *Forum on Concepts and Approaches for the Jupiter Icy Moons Orbiter* (LPI, 2003). The forum was open to the scientific community and was held at the Lunar and Planetary Institute, Houston, Texas, on 12-14 June 2003; it was attended by ~ 150 participants. The goal of the forum was to engage a large cross-section of the science community in identifying key science questions that could be addressed by the JIMO mission. At the forum the JPL JIMO Project team provided background information on the flight system concept, and representatives from NASA Headquarters discussed the structure of *Project Prometheus* and the potential science capabilities of the mission. This meeting resulted in an initial set of science goals, objectives, investigations and measurements for exploring the Jupiter system.

Following the June SDT meeting, the structure of the various theme groups was modified such that some groups were merged, with the end result providing four areas of concentration (theme leads indicated in brackets):

- Geology and Geochemistry [L. Prockter]
- Interior Science [D. Stevenson]
- Astrobiology [C. McKay]
- Jupiter System Science [K. Khurana]

To support the analysis of the SDT, two workshops were held in August 2003. The *Mission Science Accommodation Workshop* addressed issues related to potential spacecraft orbit characteristics and the ability to achieve science goals. The *Auxiliary Payload Workshop* addressed issues related to packages such as deployable probes. The reports from both workshops are provided in Appendix 2.

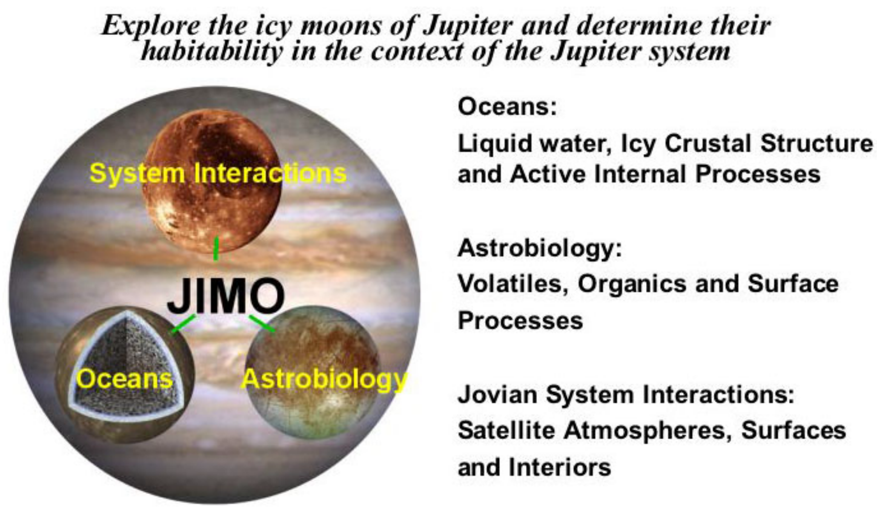

Figure 1.1. The JIMO Mission will enable the study of the icy moons in the context of the Jupiter system through themes: Oceans, Astrobiology and System interactions.

At the November 2003 meeting of the SDT, discussion led to the formulation of specific science themes for the JIMO mission. Up until this meeting, the emphasis had been on science disciplines within the sub-groups (*e.g.,* "surface geology"). By the November meeting, the SDT had arrived at a general consensus on the priority objectives and investigations within the respective discipline areas. All of the investigations were then assessed to determine if there were common cross cutting themes. The result, shown in Figure 1.1, suggested that the over-arching mission statement for JIMO is to ***Explore the icy moons of Jupiter in the context of the Jupiter system, and determine their habitability****,* which includes three themes: ***Oceans*** (verifying their existence, finding their locations, studying the structure of their icy crusts, and assessing active internal processes), ***Astrobiology*** (determining the types of volatiles and organics on and near the surfaces, and the processes involved in their formation and modification), and ***Jovian System Interactions*** (studying the atmospheres of the satellites and the interactions among Jupiter and the surfaces and interiors of the satellites).

This report presents the activities and recommendations of the SDT. Following this introduction, *Section 2* summarizes the general recommendations of the SDT. *Section 3* identifies the key science to be addressed by JIMO and is provided in the form of goals, objectives, investigations and measurements, and sets priorities within each goal. *Section 4* details some of the specifics of the spacecraft capabilities and requirements, including a discussion of the *Payload Accommodation Envelope* (PAE).

1.2 Current knowledge of the Jupiter system

The reconnaissance of the Jupiter system was provided by the successful flybys of *Pioneers 10* and *11*, and *Voyagers 1* and *2* (reviewed in books edited by Gehrels, 1976; Morrison, 1982; and Burns and Matthews, 1986) and *Ulysses* (*Science, Vol. 257, 11 Sept. 1992*). The *Galileo* orbiter and probe provided the next stage of exploration through the return of a great wealth of data on Jupiter, the small satellites and rings, and the Galilean satellites (Bagenal *et al.*, 2004).

The results from previous missions to Jupiter reveal a rich set of objects for intense exploration. Primary among these objects are the icy moons *Europa, Ganymede* and *Callisto*. All are thought to contain liquid water beneath icy surface shells. However, each of the satellites is a world in their own right. They exhibit distinctive surface histories, which probably reflect differences in exogenic and endogenic processes. Ganymede, the largest satellite in the Solar System, is nearly the size of Mars. Callisto is a Mercury-sized object. Europa, the innermost of the three, appears to experience heating derived from tidal stressing. Thus, the likely presence of liquid water, internal energy, and organic compounds derived partly from cometary implantation make Europa a high-priority target in NASA's search for life beyond Earth and an understanding of life's origin(s).

The *National Research Council* has identified the importance of Europa for exploration (NRC, 1999), especially as a target for astrobiology (NRC 2002, 2003a), and recommended it as the focus of the "flagship mission" for the coming decade of solar system exploration (NRC 2003b). It should be noted that these reports were completed before the opportunity to explore the Jupiter system and multiple satellites was afforded by a spacecraft such as JIMO. For example, in recognition of the importance of global exploration of Ganymede, the NRC (2003) report recommended an orbiter mission for Ganymede in addition to the Europa mission, but for a later period. Moreover, NASA's Office of Space Science has developed a "roadmap" for Solar System exploration, which also emphasizes the study of Jupiter's icy moons (NASA, 2003).

The new capabilities of the *Jupiter Icy Moons Orbiter* afford the opportunity for unprecedented exploration of the satellites and the Jupiter system by providing new data sets, including global mapping over a wide range of the electromagnetic spectrum. In addition to a wide variety of instruments, new classes of instruments are feasible to take advantage of the extraordinary amounts of power generated by JIMO. For example, most deep space spacecraft generate a few hundred watts of power, whereas JIMO can produce an order of magnitude greater power for instruments such as ice-penetrating radar systems. Moreover, nearly all instruments will be able to operate simultaneously, and JIMO will have the capability to transmit to Earth a greater volume of data than previous missions. Equally important will be the opportunity to change the trajectory of the spacecraft repeatedly to orbit the three moons individually. The capabilities provided by JIMO will address high-priority science issues identified by the SDT and the broad scientific community.

2.0 SDT RECOMMENDATIONS TO NASA

The *Jupiter Icy Moons Orbiter* represents an enormous investment in resources, including time and intellect. Consequently, there should be a commensurately large scientific return from the mission. The following recommendations represent the consensus view of the SDT. The recommendations begin with overall scientific goals identified for JIMO, as discussed in detail in Section 3, followed by various recommendations for implementing the science, including programmatic issues for consideration.

2.1 Science goals

The SDT recommends that JIMO be implemented to meet all science baseline and floor objectives, investigations and measurements elucidated in Section 3.

Four scientific goals are identified for JIMO: 1) determination of the geological history and composition of the icy satellites, 2) determination of the interior structure and evolution of the icy satellites, 3) study of the astrobiological potential of the icy satellites, and 4) investigations of aspects of the broad Jupiter system as they relate to the icy satellites.

2.2 Payload Accommodation Envelope (PAE)

The JIMO project should incorporate early (e.g., in Phase B) the science requirements in the design of the spacecraft, including a Payload Accommodation Envelope that has the capability for precise orbit determinations, electromagnetic cleanliness of the spacecraft, and a mass allocation of 1500 kg for science.

The Payload Accommodation Envelope should reflect the science requirements envisioned by the SDT and the potential high capability instruments enabled by JIMO. Considerations should include the ability to meet requirements of electromagnetic investigations and the orbit determination accuracies for geodetic investigations, as well as pointing and stability requirements for remote sensing. A mass allocation of 1500 kg for science was derived as follows. A comparison was made with the science payload for Cassini as a starting point. Taking into account that the JIMO PAE must also include booms, scan platforms, turntables, etc., 600 kg would barely accommodate the Cassini payload and would unlikely accommodate increased shielding, radar antennas, etc. To meet the science requirements for JIMO, new, advanced investigations must be accommodated to take advantage of the high data rates, increased power availabilities, and mission delivery capabilities. Such investigations might include high-power active laser spectrometers, super-high resolution optical and hyperspectral imaging systems, and a surface science package on Europa. Thus, the SDT recommends that the PAE mass for science be at least 1500 kg.

2.3 Europa Surface Science Package (ESSP)

The SDT strongly recommends that a surface science package for Europa be incorporated into the JIMO mission design.

The Payload Accommodation Envelope (PAE) includes the capability to accept a deployable auxiliary science package. The SDT considered several options for possible packages with respect to the high priority JIMO science objectives (Appendix 2). The SDT recommends that serious consideration be given to a modest *Europa Surface Science Package* (ESSP) that could comprise up to ~ 25% of science payload resources, in particular mass, including any necessary delivery vehicle. Such a system should be studied as part of the continuing development of JIMO. The following is a prioritized list of objectives and related measurements for a surface package;

- *Astrobiology.* In the search for signs of past or present life on Europa, *in situ* studies of surface and near-surface material are the most direct method for addressing this key science goal for JIMO. This would enable the:
    - Search for organic materials and determination of their composition(s).
    - Search for chemical patterns in any organics that might be indicative of biological origin.

- *Geophysics.* Surface measurements will enable the determination of the local thickness and characteristics of the icy crust. The combination of surface geophysical measurements and orbital data provide independent measurements and help to constrain the inversion of the geophysical data. This would include:
    - Acoustic/seismic measurements of icy crust thickness, ocean depth, and degree of present-day activity.
    - Measurements of the geophysical and mechanical properties of the ice.
    - Measurement of the magnetic field at the surface.
    - Tracking of the surface package with the orbiter as part of geodynamics investigations.

- *Geological-compositional.* The determination of the ice and non-ice elemental and mineralogical composition of the surface will provide "ground truth" for interpreting remote sensing data obtained from orbit. Specific measurements include:
    - Elemental composition
    - Mineralogical characterization, including hydrated materials
    - Physical properties, high-resolution local morphology, and the density of surface materials as well as determination of thermal and electromagnetic (EM) properties, surface processes, and radiolysis of the surface materials.

The SDT recommends that a *Europa Surface Science Package* be part of the JIMO baseline mission. If the surface science package is flown, then, the priority is to do either of the first two objectives (Astrobiology, Geophysics), with both highly desired and the Geological-compositional as lower priority. Europa surface science would address key science objectives and greatly enhance the overall science return from the mission. In recognition of the uncertainties regarding the feasibility of the ESSP, the SDT should reassess the scientific "trades" in the future.

2.4 Investigation selections

The SDT recommends that the science instruments be competitively selected and flown as Principal Investigator provided investigations.

NASA should solicit investigations through an *Announcement of Opportunity (AO)* process that invites the scientific community to develop innovative techniques to meet the key JIMO objectives. This approach fosters both competition and innovation, leading to the return of high-quality science. Both individual instruments and suites of instruments should be considered, as appropriate, to meet the science objectives.

2.5 Planetary protection

A Planetary Protection policy and implementation strategy should be established for the exploration of icy satellites.

The SDT recommends that this policy be established as soon as possible because it will impact the design of the spacecraft and potential orbits and, therefore, the science that can be achieved. The most recent recommendations from the National Research Council - *Preventing the Forward Contamination of Europa* (NRC*,* 2000) cautions,

> "Even though current information is not sufficient to conclude whether Europa has an ocean, native life, or environments compatible with terrestrial life, it is also insufficient to dismiss these possibilities at this time. Thus, future spacecraft missions to Europa must be subject to procedures designed to prevent its contamination by terrestrial organisms. This is necessary to safeguard the scientific integrity of future studies of Europa's biological potential…"

The report concludes that given uncertainties about survivability of terrestrial organisms in extreme conditions likely to be encountered on Europa, a conservative planetary protection policy must meet the highest possible levels. According to this report, the probability of contaminating Europa with a microorganism should be less than 10^{-4}. Using a combination of Viking-level cleaning and sterilization, accompanied by bioload reduction in the Europan radiation environment, the report offers a probabilistic calculation for evaluating permissible bioload but furnishes little practical guidance on how to evaluate the efficacy of sterilization procedures. The NASA Office of Planetary Protection must provide more precise guidelines that can be directly translated into spacecraft design if the recommended likelihood of 10^{-4} for contaminating Europa is to be achieved.

2.6 Interdisciplinary Scientists

The SDT recommends that NASA consider selection of Interdisciplinary Scientists (IDSs) shortly after instrument selection and during development phase.

Interdisciplinary scientists have played valuable roles on many planetary missions, including performing theoretical and modeling studies, leading correlative studies of data sets from multiple sources, and providing leadership in planning and prioritizing cross-discipline approaches to addressing science objectives. The SDT recommends that appropriate Interdisciplinary Scientist investigations be competitively selected as soon as possible after instrument selection so that they can be active and effective in developing the science plans for the JIMO mission.

2.7 Science team augmentation

The SDT recommends that NASA consider a competitively selected augmentation to the science teams 2 to 4 years prior to operations at Jupiter.

A second selection made 2-4 years prior to operations at Jupiter provides several benefits. Most importantly, a selection well before operations is necessary to ensure community involvement with the development of the various investigations, and to promote interdisciplinary studies. In addition, this selection allows participation by early-career scientists who were not able to respond to the call for payload PIs or Interdisciplinary Scientists. This ensures that NASA develops the next generation of explorers by providing valuable flight team experience for these scientists. Selection should take place no less than two years prior to operations at Jupiter to ensure adequate time for training and complete integration into the existing science team.

2.8 Outer Planets Data Analysis Program

An Outer Planets Data Analysis program should be implemented.

To prepare for JIMO and subsequent missions, a research program needs to be established immediately to support analysis by the broad planetary community of data from previous missions, such as *Voyager* and *Galileo*, and anticipated from *Cassini.* Such analyses will provide the critical insight needed for planning JIMO and subsequent mission observations. The new (2004) Outer Planets Research Program is a fundamental first step, and the program should evolve to provide a dedicated Outer Planets Data Analysis Program.

2.9 Fundamental Research Program for Outer Planets

A Fundamental Research program should be established for the Outer Solar System.

A fundamental research program for the outer solar system should be established as soon as possible to complement the recommended Outer Planets Data Analysis program by providing the broad foundation for interpreting the spacecraft data. The proposed fundamental research program would support activities such as laboratory investigations relevant to outer planet systems and the preparation of cartographic materials using existing data sets. The new Outer Planets Research Program is a critical first step, and the program should evolve to provide a dedicated fundamental research program for the outer planets.

2.10 JIMO Data Analysis Program

A JIMO Data Analysis program should be implemented.

A JIMO Data Analysis Program should be implemented immediately following the initiation of the orbital operation phase of the JIMO mission. Adequate funds must be identified in the early planning phase of the project to ensure that the scientific potential from the enormous wealth of JIMO data can be realized through analysis by the full scientific community.

2.11 JIMO Science Investigation Development and Operations

The SDT recommends that the resources for science be identified for the full life cycle of the JIMO mission.

The ultimate scientific return from the JIMO mission depends on adequate funding for all phases of the project from technology development through the data analysis and archiving stages, especially with the anticipated large data volume. The JIMO mission will require major increases in the science infrastructure supporting outer planets science. The SDT recommends that NASA develop plans for creating this infrastructure (research and analysis programs, JIMO science resources, and data analysis plans) at levels comparable to the highly successful astrophysics Great Observatories program.

2.12 Ground Data System

The SDT recommends that the JIMO project implement a ground data system to convert raw spacecraft data into useful science data products that are validated and archived.

The SDT recognizes that the complexity of JIMO is challenging and that the expected data rates are orders of magnitude higher than those of the *Galileo* or *Cassini* Projects. Because of the complexity of designing observations on shared scan platforms or turntables, one or more science planning teams should be formed. These teams would interact with the various PIs and help design and integrate the observation plans. Individual science teams will be responsible for archiving calibration data and algorithms and/or calibrated or higher level products in the PDS. While it is important to move these data to the PDS as quickly as possible, it is unlikely that proper calibration and validation can be accomplished in less than 12 months. This process should be developed and overseen by a Data Archiving Working Group including representation from all science teams, the Project, and the PDS, and should be documented. NASA must prepare the PDS for the magnitude and complexity of the data sets that will be generated by JIMO to ensure that it has sufficient resources to ingest and peer review the data sets. NASA must prepare the DSN and related infrastructure for the data rates and volumes associated with JIMO. In addition to greatly increased telemetry rates, JIMO operations are likely to use nearly continuous DSN tracking, at least during the science orbits. Hence, the additional loading factor of JIMO must be factored into the mission set forecasted for the JIMO timeframe. The potential volume of JIMO data is comparable to *Earth Observing System* missions such as *Terra.* Planning should begin early in the mission development phase to ensure the necessary infrastructure to store, manage, and deliver these data.

3.0 SCIENCE RATIONALE FOR JIMO

The SDT process included solicitation of science ideas for the JIMO mission through the *Forum on Concepts and Approaches for the Jupiter Icy Moons Orbiter*, which was open to the scientific community (LPI, 2003). The science rationale and requirements for the exploration of the Jupiter system were derived from the forum. The discussion in this section represents a comprehensive strategy for the exploration of the icy moons within the framework of the Jupiter system. To provide a firm foundation for JIMO science, the requirements flow from high-level goals and objectives to specific investigations and measurements. Four equally important goals are identified (Sections 3.1 to 3.4); within each goal, the objectives are prioritized (A, B, C, etc.) and within each objective, the investigations are prioritized (1, 2, 3, etc.). From these, the SDT has defined *baseline mission* along with a *science floor mission* (see summary in Table 3-1). The *science floor* is defined as the minimum science for a viable mission and is identified at the measurement level by boldface type.

3.1 SURFACE GEOLOGY AND GEOCHEMISTRY GOAL: To determine the evolution and present state of the Galilean satellite surfaces and subsurfaces, and the processes affecting them.

The capability of JIMO for extended orbital exploration of the moons of Jupiter will allow for significant advances in the study of their surfaces and subsurfaces and the processes affecting them. Using near-global high resolution imaging in the visible to infrared, with corresponding topographic mapping and subsurface sounding, it will be possible to determine the styles, distribution, and importance of processes that have shaped the satellites' surfaces over time. This information will provide further insight into why the evolutionary path of each moon is different. Through topographic mapping, subsurface sounding, and compositional measurements from remote sensing, it will be possible to determine the places and mechanisms by which Europa's putative ocean may communicate with the surface, and how erosional processes operate. In addition, high resolution mapping of selected areas will enable the identification of surface sites that are the most promising candidates for further exploration. Remote sensing observations of Io will provide insight into its role as a source of materials that may be implanted on the other satellites, its interactions with Jupiter's magnetosphere, and the general processes that operate on this, the most volcanically active object in the solar system.

Geology-Geochemistry Objective A: To determine the origins of surface features and the *implications for geological history and evolution, and the mechanisms of surface/subsurface interchange*

1. Investigation: Determine the styles, distribution and importance of magmatic (intrusion, extrusion) and tectonic processes (isostatic compensation, styles of faulting, flexure and folding). Magmatism and tectonism play primary roles in shaping the surfaces of the Galilean satellites. By studying the magnitudes and mechanisms of these processes, a better understanding will be obtained of how geologic activity occurs in different materials and environmental conditions, providing constraints on models of the satellites' evolution and current state.

Table 3.1 Goals, objectives, investigations, and measurements for JIMO.

		Goals and objectives											
		SURFACE GEOLOGY AND GEOCHEMISTRY		**INTERIOR SCIENCE**			**ASTROBIOLOGY**		**JUPITER SYSTEM**				
Investigations & Measurements		Geological history, mechanisms	Comp. Evolution	Location of water	Evolution of internal structure	Form evol. Jupiter system	Signs of life	Habitability	Interactions	Jupiter atm	Magnetos phere	Io interaction s	Ring system
Science Floor													
Magmatic and tectonic processes on Galilean satellites		x	o	x	x			x	o			o	
a	Topo mapping, 10m/20%	x			x								
	Global topo, 10m	o											
b	Global subsurface profiling	x		x	x			x					
c	Global mono 80%,<100m	x			o				o				
d	Io NIR image, <100km	x											
	Io IR image, <20km	o											
e	Io global color, <10km	x			o							o	
f	Io topo, 1km/100m vert	o			o								
g	Global mono, <10m	o	o		o								
Europa surface-subsurface material interchange		x		x	x			x					
a	Global subsurface profiling	x		x	x			x					
b	Topo mapping, 10m/20%	x			x								
Surface ages and subsurface structure via cratering		x	o	x	x			x	o				
a,b,e	Topo mapping, 10m/20%	x			x								
c	Global mono 80%,<100m	x			o				o				
d	Global subsurface profiling	x		x	x			x					
f	Global mono, <10m	o	o		o								
g	Global color, <100m (30m targets)	o	o		o				o				
h	Mono Amalthea Thebe, 1km	o											
i	Small satellite target of opportunity	o											
Evidence of recent surface activity		x	x	o	o	o		o					
a	Redo GLL/VGR imagery	x											
b	Europa FIR to 100um; repeated		x										
	Thermophysical map	o	o	o	o								
c	Bolometeric albedos	o	o										
d	Global topo, 10m	o											
e	Shallow subsurface regolith prop	o											
f	Global subsurface profiling	o		o	o			o					
g	Seismo-acoustic Europa Europa surface obs	o		o	o	o		o					
Surface age from erosion/deposition and energy/matter flux		x	o	o	x								
a	Topo mapping, 10m/20%	x			x								
	Global topo, 10m	o											
b	Targeted mono, 1 m & 5m context	x			o								
	Multispectral targets, 1m & 5m context	o											
c	Thermophysical map	o	o	o	o								
d	Bolometeric albedos	o	o										
e	Shallow subsurface regolith prop	o											
f	Photometeric properties map	o											
Identification & distribution of surface components		o	x		o				o			o	
a	NIR spectra, <100m, 90%		x						o				
	NIR spectra, <20m targets		o										
b	Io NIR (SO2), 20km		o										
c	NIR higher spectral res targets		o										
d	VIS spectra, <100m, 90%		o						o				
e	UV spectra, <100m, 90%		o						o				
f	Mid IR, <100m, 90%		o						o				
g	Global color, <100m (30m targets)	o	o		o				o				
h	Global mono, <10m	o	o		o								
i	Io UV spectra, <100 km		o									o	
j	Minor surface and neutrals		o										
k	Surface elemental comp Ca to C		o										
l	Vis/NIR spectra small inner satellites		o										
m	Color Amalthea/Thebe, 5m		o										
n	Small sat Vis/NIR spectral imaging, <10km		o										
Europa global heat flow		o	x										
a	Europa FIR to 100um; repeated		x										
b	Bolometeric albedos	o	o										
Extent of differentiation of the icy satellites				x	x	o		x					
a	J2 & C22, 10^{-7}			x	x			x					
b	Static topo, 10m, deg 2			x				x					
c	Global mag field, 0.1nT			x	o	o		x					
d	Pole position to 6urad			o				o					
Presence of sub-ice oceans		o		x	o	o		x					
a	k2 & h2 to 0.005			x				x					
b	Induction mag field, 0.1nT			x	o	o		x					
c	Europa libration/asynch rotation, 10m			x				x					
d	Seismo-acoustic Europa surface obs	o		o	o	o		o					
Distribution of possible liquid beneath crusts		x	o	x	x	o		x					
a	Global subsurface profiling	x		x	x			x					
b	Seismo-acoustic Europa surface obs	o		o	o	o		o					
c	Induction mag field, 0.1nT			o	o	o		o					
d	Europa FIR to 100um; repeated		o										
Thickness of ice layer		x	o	x	x	o		x					
a	Seismo-acoustic Europa surface obs	o		o	o	o		o					
b	k2 & h2 to 0.005			x				x					
c	Europa libration/asynch rotation, 10m			x				x					
d	Induction mag field, 0.1nT			x	o	o		x					
e	Global subsurface profiling	x		x	x			x					
f	Europa FIR to 100um; repeated		o										
g	Europa heat flow, <10mW/m2			o	o			o					
Evidence for current internal activity		o	o	o	x	o		o				o	
a	Seismo-acoustic Europa surface obs	o		o	o	o		o					
b	Detect 10m vert/horiz displacement				x								
	Detect 1m vert/horiz displacement				o								
c	Global subsurface profiling	o		o	o			o					
d	Global mag field, 0.1nT			o	o	o		o					
e	Europa FIR to 100um; repeated		o										
f	Io global color, <10km	o			o							o	
	Io NIR (SO2), 20km		o										
	Io UV spectra, <100 km		o									o	
	Io FIR to 100um; 30km repeated		o			o							
Evidence for internal activity on geologic time scales		x	o	x	x	o		x					
a	J2 & C22, 10^{-7}			x	x			x					
	J2 & C22, 10^{-8}				o								
b	Global subsurface profiling	x		x	x			x					
c	Induction mag field, 0.1nT			o	o	o		o					
d	Europa FIR to 100um; repeated		o										
e	Europa heat flow, <10mW/m2			o	o			o					
Biogenic organics at Europa's surface and shallow subsurface							x						
a	Organic molecules <10000 amu, Europa						x						
b	Chirality of bio molecules, Europa, 10%						o						
c	Concentrations of biomarkers, Europa, ppm						o						

Table 3.1 (continued)

Effects of magnetosphere on icy moons									x		x		
a	Continuous fields and plasma near moons								x		x		
b	Sampling neutral atmosphere								x				
c	Emission/absorption neutral atmosphere								x				
d	Atmosphere emission profiles, 5km								x				
e	Satellite auroral emissions								x				
f	Expanded fields and plasma near moons								o				
Interior structure of icy moons from electromagnetic induction									x		x		
a	Continuous fields and plasma near moons								x		x		
Jupiter atmospheric dynamics										x			
a	Jupiter Vis maps, 10km									x			
b	Jupiter NIR spectral maps, 100km, R>3000									o			
c	Jupiter ammonia dist, uwave radiometry, 5000km									o			
	Jupiter MIR spectral maps, 100km, R 10000									o			
Structure of Jovian magnetosphere											x		
a	F & P; Jupiter approach, moon transit & magnetosheath crossings										x		
b	Synchrotron radiation										o		
Magnetospheric coupling of satellites and Jupiter											x		
a	Imaging satellite auroral footprints, 100km										x		
b	Jovian aurora (xray Š IR) & magnetosphere									o	o		
c	Wind velocities from tropopause to thermosphere										o		
Baseline													
Europa high-res surface properties		o	o	o	o								
a	Targeted mono, 25cm	o											
b	Thermophysical map	o	o	o	o								
c	Bolometeric albedos	o	o										
d	Shallow subsurface regolith prop	o											
Surface chemistry processes			o						o				
a	UV spectra, <100m, 90%		o						o				
b	NIR spectra, <100m, 90%, repeated		o						o				
c	VIS spectra, <100m, 90%		o						o				
Io regional/global heat flow		o	o			o							
a	Io FIR to 100um; 30km repeated		o			o							
b	Bolometeric albedos	o	o										
Temperature-dependent stability of surface components		o	o	o	o								
a	Thermophysical map	o	o	o	o								
Place bounds on orbital evolution of the moons		o	o			o							
a	Moon secular acceleration, 5m/yr^2					o							
b	Io FIR to 100um; 30km repeated		o			o							
	Bolometeric albedos	o	o										
Sizes/states of the cores of the moons		o		o	o	o		o					
a	Global mag field, 0.1nT			o	o	o		o					
b	Seismo-acoustic Europa surface obs	o		o	o	o		o					
Iotopic fractionation in organic/inorganic compounds							o						
a	Isotope ratios, surface, ppm						o						
b	Isotope ratios, atmosphere, <10 ppm						o						
Presence of potential metobolic byproducts							o						
a	Concentration/dist biogenic gases						o						
b	Metabolic byproduct search, Europa surface, ppm						o						
Nature/distribution of abiotic organic matter			o				o		o				
a	Organic concentrations, NIR/MIR spectra, % level						o						
b	Organic molecules <10000 amu, Europa in situ						o						
Search for organisms by microscopy							o						
a	Microscopic exam of melt for organisms						o						
Composition of surface and shallow subsurface ice on Europa								o					
a	Concentrations/conductivity of major surface ions							o					
b	Concentrations of biologically relevant surface ions/elements							o					
c	Surface pH, eH							o					
d	Surface carbon concentration							o					
e	Isotopic composition of ice/organic matter, ppm							o					
Environmental resources of energy								o					
a	Concentrations of e- acceptor/donor pairs							o					
b	Concentrations of H2, CO2, CH4, H2S, ppm							o					
Radiation effects on stability of organic molecules								o					
a	Energy/global distribution of energetic e-/ions at surface							o					
b	Radiation-generated compounds on surface							o					
c	Distribution of compounds with depth on Europa							o					
Effects of particle sputtering on moons' surface/atmosphere			o						o				
a	VIS spectra, <100m, 90%		o						o				
	NIR spectra, <100m, 90%		o						o				
a,b	UV spectra, <100m, 90%		o						o				
c	x-ray imaging, 100m								o				
d	Sampling neutral atmosphere								o				
Temperature and energy balance of Jupiter										o			
a	Jupiter MIR spectral maps, 100km, R 10000									o			
	Jupiter FIR spectral maps, 100km, R>2000									o			
b	Jupiter global vertical temp structure									o			
c	Jupiter radio occultations									o			
d	Jovian aurora (xray Š IR) & magnetosphere									o	o		
Jupiter's clouds, hazes, and precipitation										o			
a	Jupiter Vis maps, 10km									o			
a,b	Jupiter NIR spectral maps, 100km, R>3000									o			
a,d,e	Jupiter MIR spectral maps, 100km, R 10000									o			
a,d	Jupiter FIR spectral maps, 100km, R>2000									o			
b	Jupiter Vis spectral/polarization maps, 100km, R>300									o			
b	Jupiter UV maps, 100km									o			
c	Jupiter NIR spectral maps, 10km, R 20-500									o			
c	Jupiter MIR spectral maps, 10km, R 20-500									o			
c	Jupiter FIR spectral maps, 10km, R 20-500									o			
f	Jupiter UV stellar/solar occultations									o			
g	Distribution of Jovian precipitation, 1000km									o			
Composition of Io's atmosphere			o									o	
a	Io UV spectra, <100 km		o									o	
Relationship of Io volcanic activity to torus and aurorae												o	
a	Io global color, <10km											o	
b	Io UV aurora/dayglow monitoring											o	
c	Io UV torus monitoring											o	
d	Io auroral footprint, UV-IR, 10km											o	
e	F & P near EuropaÕs orbit & Io monitoring											o	
Particle size distribution in each ring component													o
a	Ring system vs. phase angle, Vis/NIR images, 10km												o
b	Ring system vs. phase angle, Vis/NIR spectral cubes, 50km												o
c	Main ring, FIR spectrum												o
3-D structure of ring system													o
a	Ring system edge on vs. phase angle, Vis/NIR images, 10km												o
b	Ring halo shadow boundary, Vis/NIR, 10km												o
c	Main ring hi-res vs. phase angle, Vis/NIR, 10-km												o
Composition of rings and embedded moons			o										o
a	Inner sats VIS/NIR spectral cubes		o										o
b	Low-phase ring system, Vis/NIR spectral cubes, 10km												o
Small inner moon search													o
a	Satellite search, repeated Vis long exposures												o

x = Science Floor o = Baseline

Measurements

a. Conduct topographic mapping of a representative 20% of the surfaces of the icy satellites at better than 10-m/pixel scale, and better than or equal to 1-m vertical accuracy, including the site of a potential lander. Global coverage is desired.

b. Obtain global profiling of subsurface thermal, compositional, or structural horizons of the icy satellites, with ≤ 5 degree equatorial spacing, at depths of 2- to 30-km at 100-m vertical resolution, and at depths of 100-m to 2-km at 10-m vertical resolution. Multiple ground tracks over features of interest are needed.

c. Obtain global (>80%) monochromatic imaging of the icy satellites at 100-m/pixel scale.

d. Obtain hemispheric IR images of thermal emission from Io at < 100-km/pixel scale for wavelength bands of 1- to 5-microns and a spectral resolution > 10 on frequent temporal scales (e.g. hourly, daily, weekly, and monthly during transfer between satellites). Desire imaging as frequently as possible, and < 20-km/pixel scale at the equator.

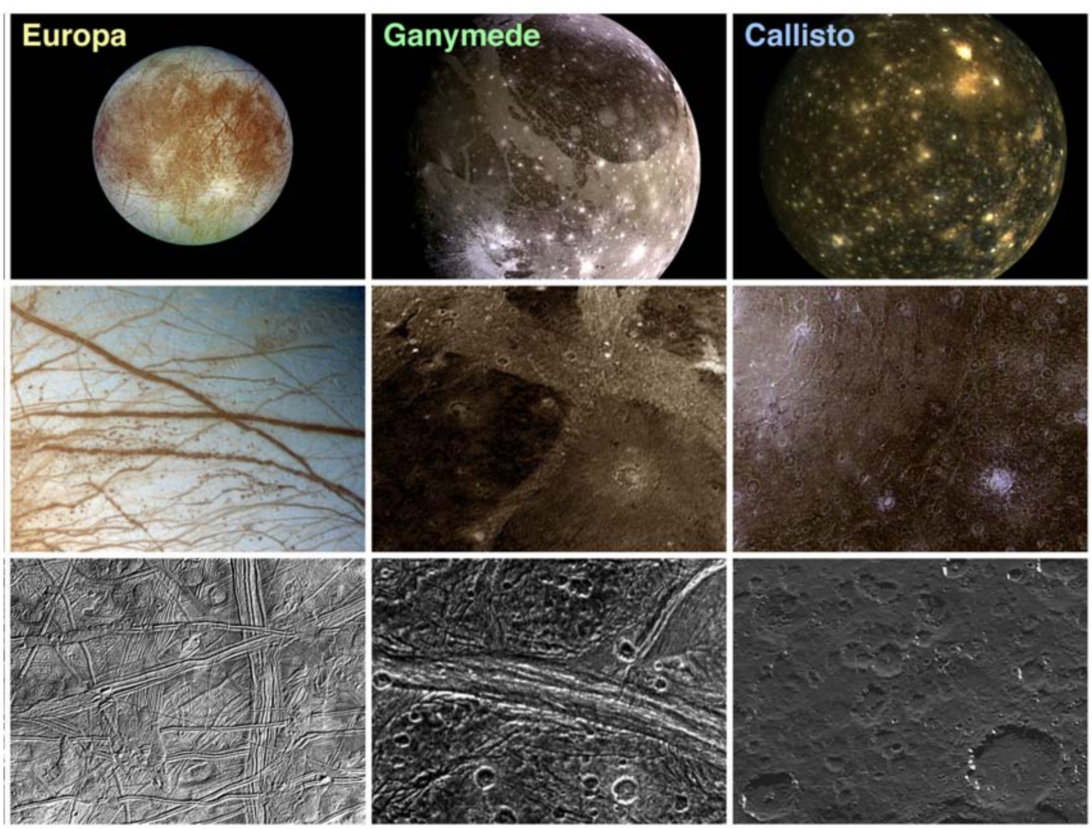

Fig. 3.1. Global, regional and local view of the icy Galilean Satellites. In the top row of images, the smallest features that can be seen are about 20 kilometers in size. In the middle row the picture resolutions are up to ten times higher. The bottom row displays views typical of the highest resolutions that have been achieved (up to about 20 meters). Data collected by JIMO will allow the study of surface composition and properties at a range of scales.

e. Obtain frequent global (>80%) multispectral mapping (minimum 3 colors) of Io at better than or equal to 10-km/pixel scale at the equator in violet, green, and IR wavelengths over a range of temporal scales (*e.g*. hourly, daily weekly, monthly).

f. Map global (>80%) topography of Io with 1-km horizontal and 100-m vertical resolution.

g. Obtain monochromatic (albedo) global (>90%) mapping of the icy satellites at better than or equal to 10-m/pixel scale with phase angles less than 30˚ (as near as possible close to poles); include the site of a potential surface package on Europa at 1-m/pixel ground sampling.

2. Investigation: Test for the existence and means of surface-subsurface interchange of material on Europa. Study of geological and geochemical processes can determine whether Europa's ocean communicates directly (*e.g.,* by melting) or indirectly (*e.g.*, via ice diapirs or brine pockets) with the surface. The method of communication has implications for Europa's evolution and astrobiological potential.

Measurements

a. Obtain global profiles of subsurface thermal, compositional, or structural horizons at ≤ 5 degree equatorial spacing, at depths of 2- to 30-km at 100-m vertical resolution and at depths of 100-m to 2-km at 10-m vertical resolution. Multiple ground tracks over features of interest are needed.

b. Conduct topographic mapping at 10-m horizontal and 1-m vertical resolution for the same locations profiled for subsurface thermal, compositional, and structural horizons.

3. Investigation: Assess surface ages and subsurface structure using impact crater morphology, and size frequency distributions. Impact craters provide a window into the subsurface structure and composition of planetary bodies. In addition, their distribution provides information into how the number of impactors in a system has changed over time, and the processes that have occurred on a body during its history.

Measurements

a. Conduct topographic mapping at 20% coverage of the icy satellites at better than 10-m pixel scale, and better than 1-m relative vertical accuracy. Global coverage is desired.

b. Conduct targeted topographic mapping of craters on the icy satellites and surrounding terrains at 10-m pixel scale, and better than 1-m relative vertical accuracy.

c. Obtain global (>80%) monochromatic images of the icy satellites at better than 100-m/pixel scale.

d. Conduct global profiling of subsurface thermal, compositional, or structural horizons, at ≤ 5 degree equatorial spacing, depths of 2- to 30-km at 100-m vertical resolution and depths

of 100-m to 2-km at 10-m vertical resolution. Multiple ground tracks over features of interest are needed.

e. Conduct topographic mapping at 10-m horizontal and 1-m vertical resolution for the same locations profiled for subsurface thermal, compositional, and structural horizons.

f. Obtain monochromatic (albedo) global (>90%) mapping of the icy satellites at better than 10-m/pixel scale with phase angles less than 30˚ (as near as possible close to poles).

g. Conduct multispectral (violet, green, IR) global (>90%) mapping (minimum 3 colors) of the icy satellites at better than 100-m/pixel scale. Selected areas better than 30-m/pixel scale with phase angles < 30˚ (except near poles).

h. Obtain monochromatic images at 1-km/pixel scale of inner satellites Amalthea and Thebe.

i. Obtain monochromatic images for any small satellite that is a target of opportunity.

4. Investigation: Search for surface changes and geological evidence of recent activity. By searching for changes or other evidence of activity on the surfaces of planetary bodies during JIMO operations, and by comparing images and other data with those obtained from previous missions, likely places of current geological activity can be identified.

Measurements

a. Obtain images of areas seen on previous missions (preferably with similar lighting geometry) for the Galilean satellites.

b. Map regolith thermophysical properties in the 8- to 50-μm wavelength range with spectral resolution of 2 and spatial scale of ≤ 300-m/pixel, and 90% coverage; repeat observations several times of day and night for Europa, Ganymede, and Callisto.

c. Map bolometric albedo at the wavelength range of 0.3- to 3-μm; under broad illumination geometry for the Galilean satellites.

d. Obtain repeated topographic mapping at 10-m/pixel horizontal scale and 1-m/pixel vertical resolution on orbital timescales (*e.g.*, search for motion along fractures) for Europa.

e. Map the subsurface (> 1-m) heterogeneity of the regolith at wavelengths of 10- to 30-cm, at better than 100-m horizontal resolution, with minimum swath width of 50-km covering greater than 50% of Europa, Ganymede and Callisto.

f. Obtain repeated subsurface profiling of the upper 2-km at 10-m resolution for the icy moons.

g. Measure the three-axis seismic motion on Europa with a dynamic range of 10^3 to 10^{-5} μm/s over several diurnal cycles on Europa. The frequency range should be 0.01 to 100 Hz.

5. Investigation: Investigate erosion/deposition processes (impact gardening, sputtering, mass wasting, frosts), and their relationship to fluxes of energy and matter into and out of icy satellite surfaces, and the application of the results for relative or absolute surface age determination. Local processes can have a significant effect on the thermal, spectral, and structural properties of a body's surface. By studying these processes the environment and evolution of the Galilean moons can be better understood.

Measurements

a. Conduct topographic mapping of 20% of the icy satellites at better than 10-m/pixel scale, and better than 1-m relative vertical accuracy. Global coverage is desired.

b. Obtain monochromatic images of selected target areas of the icy moons at ~1 meter/pixel scale and 60°-75° solar incidence, and with 5-meter/pixel lower-resolution context. Desire multispectral imaging.

c. Map regolith thermophysical properties in the IR (wavelength range of 8- to 50-μm) with a spectral resolution of 2 and a spatial resolution of ≤ 300-m covering 90% of the icy satellites. The observations should be at different times of the day. Repeated coverage at night is especially necessary.

d. Map bolometric albedo at a wavelength range of 0.3- to 3-μm with broad illumination geometry and precise absolute calibration for the Galilean satellites.

e. Map the subsurface (depths below > 1-m) heterogeneity of the regolith at wavelengths of 10- to 30-cm, at 100-m horizontal resolution, with minimum swath width of 50-km covering at least 50% of Europa, Ganymede and Callisto.

f. Map regolith photometric properties of the icy moons in the wavelength range of 0.3- to 3-μm with a spectral resolution of 2; broad illumination geometry coverage, good absolute calibration

6. Investigation: Study the surface of Europa at spatial scales relevant to regolith properties and landing hazards. By mapping the surface of Europa at very high resolution, the regolith can be studied at small scales relevant to properties such as its thermal and physical structure, and potential hazards for future landed missions can be identified.

Measurements

a. Obtain super-high resolution monochromatic images of selected areas on Europa (with intermediate context imaging) down to 25-cm/pixel scale at incidence angles of ~60°-75°.

b. Map regolith thermophysical properties of Europa in the thermal wavelength range of 8- to 50-μm with spectral resolution of 2 and spatial scale of ≤ 300-m/pixel, and 90% coverage; repeat observations several times of day and night.

c. Map bolometric albedo of Europa at the wavelength range of 0.3- to 3-µm; broad illumination geometry coverage.

d. Map the subsurface (>1-m) heterogeneity of the regolith at wavelengths of 10- to 30-cm, at better than 100-m horizontal resolution, with minimum swath width of 50-km covering at least 50% of Europa, Ganymede and Callisto for inter-comparisons.

Geology and Geochemistry Objective B: *To determine the integrated compositional evolution of the Jovian satellites through measurement of the composition, physical state, and distribution of surface materials.*

1. Investigation: Identify major and minor surface components and their distributions, including organic molecules and trapped volatiles; requires observations on a global scale at a resolution comparable to the scale of the geological processes. The first step in assessing compositional evolution is to understand the current chemical state of the surfaces of the icy satellites. The abundance and distribution of ice, ice crystallinity, organics, radiation products, and salts needs to be mapped to understand these complex surfaces.

Measurements

a. Make near-IR observations to detect various chemical species in the wavelength range of 1- to 5-µm with a spectral resolution of 300 and a spatial scale of < 100-m/pixel covering 90% of the icy satellite surfaces and at 10- to 20-m/pixel scale for targeted locations.

b. Make near IR observations of Io (measuring primarily SO_2) daily or more frequently (if possible) in the wavelength range of 1- to 5-µm with a spectral resolution of 300 and a spatial scale < 20-km/pixel.

c. Obtain near IR observations to identify hydrated materials in the wavelength range of 1.2- to 2.5-µm with a spectral resolution of 1000, a spatial scale of < 100-m/pixel and coverage of 5% for targeted locations of the icy satellites.

d. Make visible wavelength observations to measure O_2 and coloring agents in the wavelength range of 0.4- to 1.0-µm with a spectral resolution of 300 (most important for O_2 bands at 0.55- to 0.65-µm) and a spatial scale < 100-m/pixel and coverage of 90% of the icy satellites.

e. Make observations to measure of SO_x, O_3, H_2O_2, and OH in the wavelength range of 0.2- to 0.4-µm with a spectral resolution of 40 and a spatial scale < 100-m/pixel covering 90% of the icy satellites.

f. Obtain mid IR measurements of fundamental modes of organics, salts and silicates in the wavelength range of 5- to ≥ 10-µm with a spectral resolution of at least 200 and a spatial scale of < 100-m/pixel covering 90% of the icy satellites.

g. Obtain multispectral global mapping of the icy satellites in a minimum of 3 colors (violet, green, IR) at better than 100-m/pixel scale and selected areas at 30-m/pixel scale with phase angles < 30˚ (except near poles).

h. Obtain monochromatic global (albedo) mapping of the icy satellites at better than 10-m/pixel scale, and phase angle < 30˚ (as near as possible close to poles).

i. Obtain atmospheric spectroscopy of Io to measure SO_2, S_2 in the wavelength range of 0.2- to 0.4-μm with a spectral scale of 400 and a spatial scale < 100-km/pixel for global coverage repeated daily.

j. Determine the minor surface species and superthermal neutral species in satellite atmospheres to a sensitivity of $< 10^6$ cm^{-2} s^{-1} over a mass range > 1500 Dalton, a mass resolution of $m/\Delta m$ of 300 at 10% of peak height and an angular resolution of 5° by 5°.

k. Determine the surface composition of elements from carbon to calcium (by atomic weight) on the icy moons with a Full Width Half Maximum (FWHM) field of view of 6°.

l. Image in the visible and near IR the inner small satellites at a spectral resolution of 300.

m. Obtain visible color (three or more colors) images of Amalthea and Thebe at a spatial scale of 5-km/pixel.

n. Obtain visible and near IR images of small satellites as targets of opportunity at a spectral resolution of 300 and at least 10-km/pixel scale.

2. Investigation: Investigate local and global heat flow on Europa to study its thermal evolution. Areas of recent resurfacing and areas of enhanced heat flow would provide locations where surface/subsurface interactions have occurred. This knowledge would provide insights into the composition of the interior, and timescales and mechanisms of surface/subsurface interactions.

Measurements

a. Conduct thermal mapping in the wavelength range of 8- to 100-μm with a spectral resolution of 2 and spatial scale of ≤ 300-m/pixel covering 90% of Europa and repeat the observations at several times of day and night.

b. Map the bolometric albedo of Europa in the wavelength range of 0.3- to 3-μm for broad illumination coverage.

3. Investigation: Study exogenic and endogenic processes and search for the presence of short-lived species and chemical disequilibrium via spatial distribution patterns or other characteristics, such as the time variability on diurnal or longer timescales of surface chemistry. Separating the chemical signatures of endogenic processes and radiation and externally introduced meteoritic materials is critical in defining the chemical cycles of the icy moons. Temporal changes are important in understanding the kinetics and stability of these species.

Measurements

a. Make observations of the icy moons to measure SO_x, O_3, H_2O_2, and OH in the wavelength range of 0.2- to 0.4-μm with a spectral resolution of 40 and a spatial scale < 100-m/pixel and covering 90%.

b. Conduct near IR observations of the icy moons for spectrally active species in the wavelength range of 1- to 5-μm with a spectral resolution of 300 and a spatial scale of < 100-m/pixel coverage of 90%; make repeated observations several times of day.

c. Obtain visible wavelength observations to measure O_2 and coloring agents in the wavelength range of 0.4- to 1.0-μm with a spectral resolution of 300 (most important for O_2 bands at 0.55- to 0.65-μm) and a spatial scale < 100-m/pixel covering 90% of the icy moons.

4. Investigation: Determine regional and global heat flow on Io to investigate the coupling of its thermal/orbital evolution to those of the icy satellites. Io's heat flow is an important parameter in defining the energy available from tidal dissipation in the entire system and for modeling the energy available for Europa.

Measurements

a. Make thermal maps of Io in the wavelength range of 8- to 100-μm with a spectral resolution of 2 and spatial scale of ≤ 30-km/pixel several times of day and night.

b. Make bolometric albedo maps of Io in the wavelength range of 0.3- to 3-μm with broad illumination geometry.

5. Investigation: Determine temperature-dependent physical and chemical stability of surface components (*e.g.* to determine sublimation rates, chemical reaction rates). Low temperature volatiles and ice phases are temperature dependent. Understanding the temperature distribution and the relationship to these phases will enable the modeling of transport mechanisms and the stability of surfaces.

Measurement

a. Map surface temperature distributions of the icy moons in the IR wavelength range of 8- to 50-μm with a spectral resolution of 2 and spatial scale of ≤ 300-m/pixel covering 90% of the surfaces; repeat observations several times of day and night and with high latitude/polar coverage to search for cold traps for volatiles.

3.2 Interior Science Goal: To determine the interior structures of the icy satellites in relation to the formation and history of the Jupiter system, and the potential "habitability" of the moons.

The primary objective in meeting this goal is to determine the presence and location of liquid water beneath the moons' icy crusts. This will involve understanding the extent of the satellites' differentiation, establishing whether they contain subsurface oceans, characterizing and mapping the location of possible water and brines, and measuring the thickness of the ice overlying any putative oceans. Geophysical methods (gravity, altimetry, magnetic field) are the primary means of making a global estimate of ice thickness. These techniques will be greatly enhanced by making seismic measurements on the surface. A secondary objective is to assess the active processes that have caused the moons to evolve internally. This objective involves searching for evidence of current and past internal activity, as reflected by gravitational and magnetic fields, topographic and subsurface changes, and evidence of thermal anomalies. A tertiary objective is to understand the formation and evolution of the Jupiter system by investigating the composition of Jupiter's deep atmosphere, and by placing bounds on the orbital evolution of the satellites by studying the orbital and rotational dynamics of all four large satellites, including measuring the rate at which Io dissipates tidal energy in the form of heat.

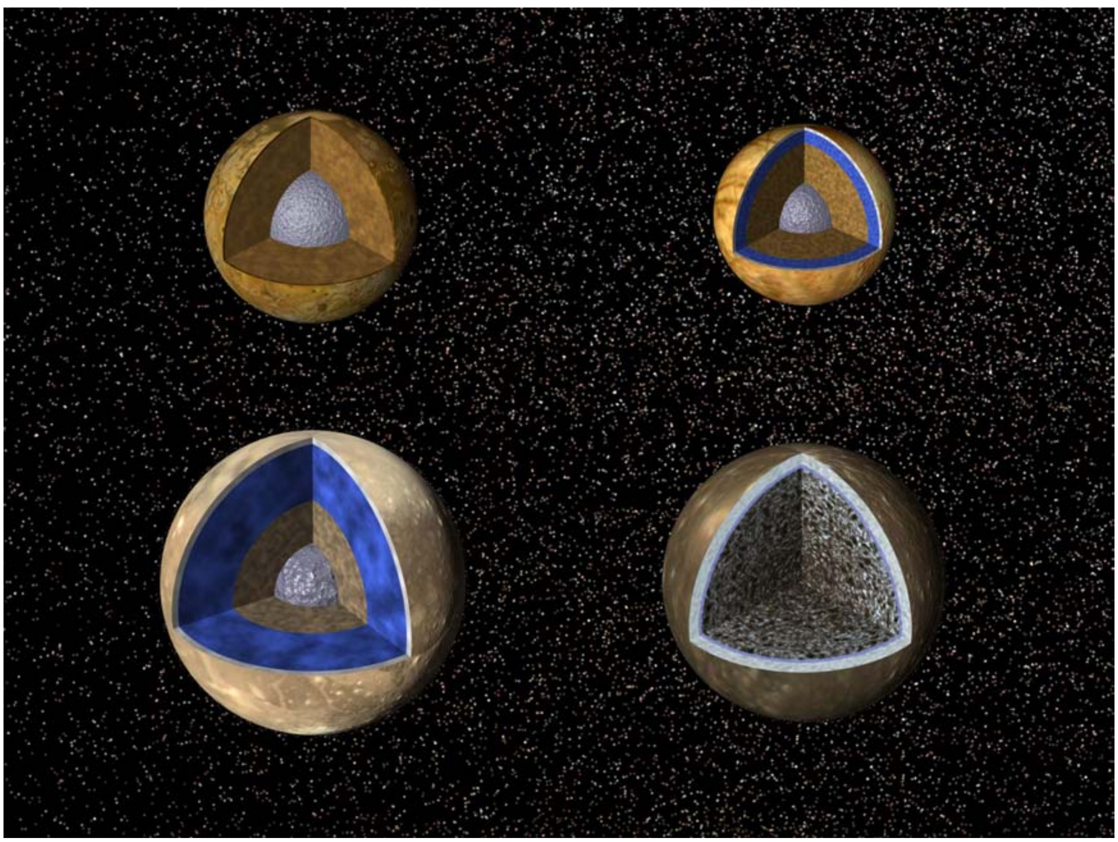

Fig 3.2. Cutaway views of the possible internal structures of the Galilean satellites. Ganymede is at the lower left, Callisto at the lower right, Io on the upper left, and Europa on the upper right. JIMO geophysical investigations will provide a means to evaluate the presence and extent of water in the subsurface of the icy Galilean satellites.

Interior Objective A: To determine the presence and location of water in the icy moons.

1. Investigation: To determine the extent of differentiation of the icy satellites. Understanding the way in which icy satellites accrete and evolve is central to understanding the history and potential habitability of their potential oceans.

Measurements

a. Measure low-order gravity (static & dynamic) J_2 and C_{22} to place constraints on non-hydrostatic components from higher harmonics and test of hydrostaticity at 10^{-7} accuracy for the second-degree non-dimensional gravitational harmonics on the icy moons.

b. Determine the degree-2 static topography to at least 10-m vertical accuracy on the icy moons.

c. Map the global magnetic field of each satellite at an accuracy of 0.1-nT.

d. Measure the pole position to 6-μrad angular accuracy to determine the obliquity of the spin axis of the icy moons. If the shell is decoupled this would provide a constraint on the shell thickness through the Cassini relation.

2. Investigation: To establish the presence of sub-ice oceans in the icy moons. Liquid water is necessary for life as we know it, and a definitive identification of an ocean within any of the icy satellites

Measurements

a. Determine the time-dependent altimetry and gravity through measurements of surface motions that correlate with the eccentricity tidal potential to 1-m accuracy and a determination of the time dependent degree-2 gravitational acceleration to 0.1-mgal at Ganymede and Callisto and 1-mgal at Europa. Alternatively, determine the eccentricity tidal k_2 and h_2 at an accuracy of 0.01.

b. Measure the induced magnetic field by determining the induction response at satellite orbital and Jupiter rotation time scales to an accuracy of 0.1-nT for the icy moons.

c. Determine the libration amplitude to 10-m vertical accuracy for Europa.

d. Measure the three-axis seismic motion on Europa with a dynamic range of 10^3 to 10^{-5} μm/s over several diurnal cycles on Europa. The frequency range should be 0.01 to 100 Hz..

3. Investigation: To determine the distribution of possible liquid (including brines) beneath the crusts of Europa, Ganymede and Callisto. Liquid water or brines trapped in the ice are indicators of the thermal and chemical state of the ice shell, and may also provide a means of transporting nutrients to the ocean, or oceanic material to the surface. Habitats may also exist in isolated pockets of liquid water.

Measurements

a. Obtain global sub-surface profiles of thermal, compositional and structural horizons for Europa, Ganymede, and Callisto's icy shells at ≤ 5 degree equatorial separations for depths

from 2- to 30-km at 100-m vertical resolution, and at depths from 100-m to 2-km at 10-m vertical resolution.

b. Seismology. (This is the same as Investigation 2, Measurement d, but with the intent of studying the structure that is not a global horizon).

c. Magnetic field. (Same requirements as Investigation 2, Measurement b).

d. Heat flow by thermal IR. (see Geology and Geochemistry, Objective B, Investigation 2, Measurement a).

4. Investigation: To determine the thickness of the ice layer for Europa, Ganymede, and Callisto. The thickness of the ice crusts of the icy satellites controls the rate of material exchange between the surface and the ocean and influences the transport of heat from the interior. Future exploration of these oceans will also depend on the thickness of the overlying ice.

Measurements

a. Determine the seismological response of Europa's shell. (See Investigation 2, Measurement d)

b. Obtain surface altimetry (in combination with gravity) to determine the eccentricity of tides to 1-m accuracy; this includes but is not restricted to degree-2 response; determine k_2 and h_2 to accuracy of 0.005 at all the satellites. In terms of percentage uncertainty in the result, this is a higher measurement requirement at Europa than at the other icy moons.

c. Determine the libration amplitude and possible asynchronous rotation to 10-m accuracy for Europa on the timescale of the mission.

d. Determine the induced magnetic field at periods from Jupiter's rotation to several week (same measurement requirement as Investigation 1, Measurement c).

e. Conduct sub-surface sounding at Europa by global profiling (measurement requirements stated in Investigation 3, Measurement a).

f. Measure heat flow using thermal IR remote sensing (see Investigation 3, Measurement d).

g. Obtain in situ heat flow on Europa to better than 10 mW/m^2.

Interior Objective B: *To identify the dynamic processes that cause evolution of the interior structure of the moons.*

1. Investigation: To find evidence for current internal activity on time scales of the JIMO mission. Geologic and volcanic activity allow the transport of material and energy within the icy moons. Current activity may be reflective of the rates of such transport and locations of such activity are potentially interesting targets for future investigations.

Measurements

a. Determine the level of seismic activity of Europa (see Objective A, Investigation 2, Measurement d) and correlate it with tidal driving stresses.

b. Determine topographic change arising from internal processes by measuring vertical or horizontal displacements of 10-m. Baseline requirement is 1-m.

c. Detect subsurface change (see Objective A, Investigation 3, Measurement a).

d. Assess magnetotelluric effects from ocean currents (sensitivity as previously indicated in Objective A, Investigation 1, Measurement c).

e. Measure heat flow by thermal IR (sensitivity as previously indicated in Objective A, Investigation 3, and Measurement d).

f. Monitor Io: (see geology section priorities).

2. Investigation: To search for evidence of internal activity on geologic timescales. Longer term activity within the satellites reflects their ongoing thermal and chemical evolution and in particular the history and future of their oceans. This overlaps with the Geology and Geophysics Objective A, Investigation 4.

Measurements

a. Obtain gravity measurements to 1 part in 10^7 and topography to 1-m to spherical harmonic degree-10. Baseline is gravity to 1 part in 10^8 and same for topography.

b. Determine thermal and compositional horizons (same requirements as Objective A, Investigation 3, Measurement a).

c. Measure magnetic field; same requirement as Objective A Investigation 1 measurement c, but with the emphasis on looking for secular variation of the "steady" field or variation in the induction signal since *Galileo*.

d. Determine upper limit on heat flow using thermal IR remote sensing (see Objective A, Investigation 3, Measurement d).

e. Determine *in situ* heat flow (see Objective A, Investigation 4, Measurement g).

Interior Objective C: *To characterize the formation and chemical evolution of the Jupiter system.*

1. Investigation: To place bounds on the orbital evolution of the moons. The energy driving Io's volcanic activity comes from its orbital evolution, and this energy source may be important for Europa and Ganymede as well. A measurement of the rate of orbital evolution at present will improve our understanding of the evolution of all four moons as well as providing estimates of the amount of energy available to drive internal activity.

Measurements

a. Determine the secular acceleration of the Galilean satellites to 5 m/yr^2 (corresponds to approximately a few meters in orbit location).

b. Assess Io heat flow constraints (same measurement requirement as that listed by Geology and Geochemistry).

2. Investigation: To determine the sizes and states of the cores of the moons. The formation of metallic cores in bodies the size of the Galilean satellites is not well understood and reflects the early evolution of the moons. Ganymede's core is probably molten, providing important constraints on its thermal history. The extent of Callisto's differentiation is not understood and may reflect its different orbital history.

Measurements

a. Determine global steady and time-varying magnetic fields (see Objective A, Investigation 1, Measurement c).

b. Measure seismicity for Europa (see Objective A, Investigation 2, Measurement d).

3.3 ASTROBIOLOGY GOAL: To search for signs of past and present life and to characterize the habitability of the Jovian moons with emphasis on Europa.

The JIMO mission provides a unique opportunity to seek evidence of biotic or prebiotic activity in an extraterrestrial environment. Liquid water is essential for all known living systems and the icy satellites may contain some of the largest reservoirs in our solar system. Whether or not icy satellites have ever provided an abode for biotic or prebiotic activity has important implications for understanding the origin and destiny of life. The detection of signs of past or present life will require measurements of certain biogenic organics with specific biological patterns and chirality or specific biomarkers known to be relevant to life. Life forms also cause isotopic fractionation of atoms that constitute biomass. In addition, life generally leads to chemical disequilibrium in the environment and, thus, *in situ* or remote sensing of metabolic byproducts can help detect signs of life. To evaluate habitability it is important to determine the presence of liquid water, the concentration of major biologically relevant ions as sources of energy and nutrients, and the potential effects of radiation on life forms

Astrobiology Objective A: *To search for signs of life (past or present) on Europa and other icy moons*

1. Investigation: Search for biogenic organics at the surface and shallow (< 1-m) subsurface at Europa. Organics that derive from biological processes are distinct from organics derived from non-biological processes in several aspects. First, biology is selective and specific in its use of molecules. For example, Earth life uses 20 left-handed amino acids. Second, biology can leave characteristic isotopic patterns. Third, biology often produces large complex molecules in high concentrations, for example lipids. These constitute the "signs of life" that we may detect on Europa.

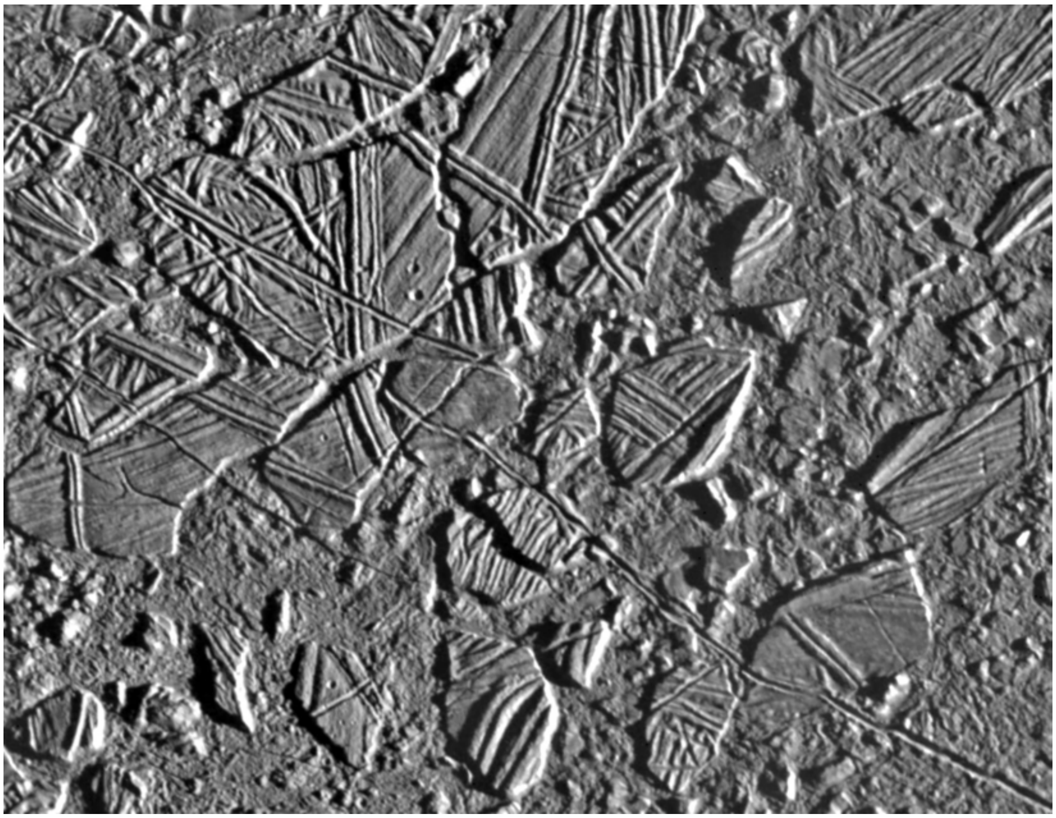

Fig. 3.3. High resolution image showing crustal plates on Europa ranging up to 13 kilometers (8 miles) across, which have been broken apart and 'rafted' into new positions, superficially resembling the disruption of pack-ice on polar seas during spring thaws on Earth. The size and geometry of these features suggest that motion was enabled by ice-crusted water or soft ice close to the surface at the time of disruption. JIMO will investigate biological potential of areas on Europa where liquid water may have reached the surface .

Measurements

a. Search for and identify key organic compounds and their molecular distribution in order to identify possible biological patterns, for example by determining the mass spectrum of organic molecules up to masses of ~ 10,000 AMU down to concentrations of < 1 ng C/l (or equivalent).

b. Search for, and determine the chirality of key molecules of biological interest including sugars and amino acids to within ± 10%.

c. Determine concentrations of specific biomarkers known to be relevant to life on Earth. These include lipids, carbohydrates, proteins (including functional domains), nucleic acids and fluorescent co-factors at the ppm level.

2. Investigation: Study the isotopic fractionation in organic and inorganic compounds due to both abiotic and biotic processes. Terrestrial biota produce distinct and measurable fractionation of the isotopic ratios of carbon, hydrogen and other biologically relevant elements. Such measurements may be one of the key identifiers found in chemical compounds in extraterrestrial environments that help delineate biotic from abiotic compounds.

Measurements

a. Measure carbon, nitrogen, oxygen, hydrogen, sulfur, iron, manganese isotope ratios in a broad range of organic molecules and inorganic surface residues to search for patterns in isotope distributions that could reflect biological fractionation processes at a precision of 1 per mil.

b. Measure $^{12}C/^{13}C$, $^{14}N/^{15}N$, $^{16}O/^{18}O$, and H/D ratios in atmospheric compounds such as CO_2, CH_4, H_2O, NH_3, H_2S, etc. (accuracy on the order of 1 to 10 per mil) as potential indicators of metabolic activity.

3. Investigation: Search for the presence of potential metabolic byproducts on all the icy satellites. Known chemotrophic life requires a chemical energy source to drive metabolic processes. Metabolism extracts energy from non-equilibrium reactants and forms traceable byproducts that may identify metabolism in the local environment.

Measurements

a. Measure the concentration and spatial distribution of key biogenic gases CH_4, H_2S, NH_3 at partial pressures of 10^{-4} Pa (ppb at 1 atm.) on the icy moons.

b. Make *in situ* measurements of the metabolic byproduct concentration and characteristics (molecular weight and structure) in surface deposits on Europa at the ppm level.

4. Investigation: Determine the distribution and nature of abiotic organic matter on Europa, Ganymede, and Callisto for comparison with potential biogenic organic compounds. The outer solar system appears to be rich in organics either through endogenous or exogenous sources of material. The identification of organic compounds on the surface of all the moons will provide a context for the identification of the organic material. Similarities and differences between Europa, Ganymede, and Callisto will help to determine if organic material has a biotic or abiotic origin.

Measurements

a. Obtain remote sensing data in the near-mid IR wavelength range of concentrations of organics (C-H bonds) in surface layers for the icy moons to the percent level.

b. Make *in situ* measurements of concentration and characteristics (molecular weight and structure) of organic matter in surface deposits on Europa at the ppm level.

5. Investigation: Search for organisms by microscopy. Well-defined membrane-type boundaries are characteristic of all terrestrial cellular organisms. Microscopy with sufficient size resolution would be the optimal technique to detect this characteristic in surface materials.

Measurements

a. Conduct optical and fluorescence microscopic examinations of processed (filtered, concentrated) melt water over 0.2- to 1000-μm size range.

Astrobiology Objective B: To determine the habitability of Europa and other icy moons of Jupiter.

Europa is one of the few worlds in the solar system that may contain liquid water and may therefore be habitable. There may also be oceans on the other ice moons and possible habitable conditions. The key for determining the habitability is to understanding the distribution of liquid water.

1. Investigation: Determine the presence and distribution of water (including brines) in three-dimensions near the surface and within Europa and the other icy moons. Europa is one of the few worlds in the solar system that may contain liquid water and may therefore be habitable. There may also be oceans on the other ice moons and habitable conditions. The key for determining the habitability is to understand the distribution of liquid water, which includes distribution of brine pockets inside the icy lithosphere.

Measurements

See specific investigations in the Surface Geology and Interior science sections (Geology Objective B Investigation 1 Measurement a and Interior Science Objective A Investigations 2 and 3).

2. Investigation: Study the composition of surface and shallow (< 1-m) subsurface ice on Europa. The composition and concentrations of dissolved ions, which include potential nutrient sources, and organic matter in the surface ice needs to be constrained to further characterize the environment on the icy moons

Measurements (primarily in situ)

a. Measure concentrations of major ions (Na^+, K^+, Ca^{2+}, Cl^-, SO_4^{2-}, Si^{4+}, alkalinity) and bulk conductivity down to the part per thousand level to precision of ±10%.

b. Measure concentrations of biogenic or biologically relevant ions (NO_3^-, NH_4^+, PO_4^{3-}) and trace elements (Zn, Cu, Mn, Fe, etc.) down to the part per thousand level to a precision of ± 10%.

c. Measure pH to ± 1 pH unit and eH to ±100 mv.

d. Measure concentrations of dissolved, particulate and total organic carbon down to the ppm level to precision of ±10%.

e. Measure isotopic composition of ice and organic matter (C, H, N, O, P, S) to precision of ± 1 to 10 per mil..

3. Investigation: Determine environmental resources of energy. Chemical energy sources of known terrestrial life include the oxidation of organic molecules with oxygen and other electron acceptors (aerobic and anaerobic respiration, fermentation) or the oxidation of inorganic molecules (chemoautotrophy). Photosynthesis as a source of energy is unlikely because of inadequate solar radiation near the surface of the icy moon.

Measurements

a. Measure concentrations (at nano-molar levels) of electron acceptor/donor pairs such as Fe^{3+}/Fe^{2+}, H_2S /S/SO_2 and oxygen concentrations.

b. Measure concentrations of H_2, CO_2, CH_4, H_2S to a precision of 1 ppm.

4. Investigation: Study the effects of the radiation environment on stability of organic molecules and on the potential habitability of the icy moons. High levels of ionizing radiation stemming from Jupiter's magnetosphere place a constraint on the habitability of the surface of the icy moons and will affect stability of possible biosignatures. Therefore it is necessary to quantify and map the distribution of energetic ions and electrons impacting on the surface, as well as determine the distribution of radiolysis products on the surface and the shallow subsurface where radiation effects might be attenuated.

Measurements

a. Measure the energy and spatial distribution of energetic electrons and ions on the surface of the icy moons, including electrons from 10 KeV to 100 MeV, heavy ions from 10 KeV to 50 MeV/nucleon, and protons from 10 KeV to 100 MeV, all with an accuracy of 10% in energy and flux. Measurements to be made at a spatial resolution of 5 degrees in sub-spacecraft latitude and longitude over the global surface of the moons, with a measurement-by-measurement time resolution of 1 per second.

b. Characterize radiation-generated compounds on the surfaces of the icy satellites to detect 1 Grad of damage.

c. Characterize the distribution of inorganic and organic compounds as a function of depth (to ~1-m) on Europa to resolve gradients of 10% /m.

3.4 JUPITER SYSTEM SCIENCE GOAL: To determine how the components of the Jovian system operate and interact, leading to the diverse and possibly habitable environments of the icy moons.

The planet, satellites, rings, dust, gas, particles and fields in the Jupiter system influence each other through many complex interactions. Understanding these interactions provide insight into the characteristics of other bodies in the Solar System. Measuring Jupiter's elemental abundance ratios will help determine the nature, history, and distribution of volatile and organic compounds in the Solar System. Understanding of the dynamics of Jupiter's atmosphere and magnetic field provide insight into the deeper structure of Jupiter.

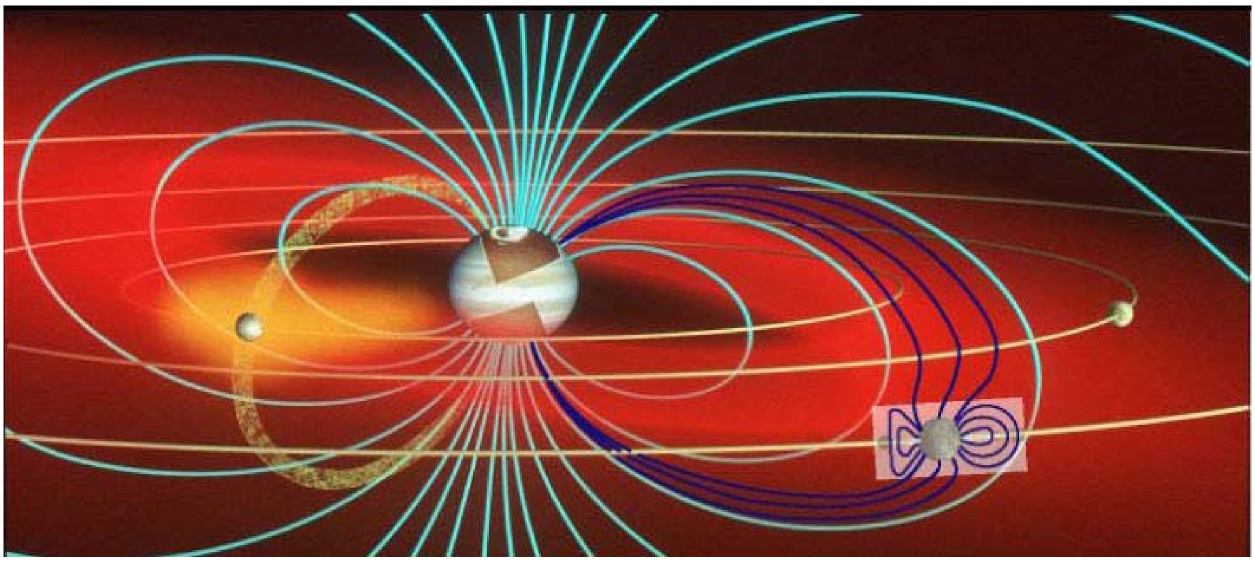

Fig. 3.4. JIMO will investigate the relation between the Galilean satellites and the Jovian environment, providing additional information in evaluating the potential habitability of these worlds.

The icy moons interact with Jupiter's magnetosphere through charged particle bombardment, which modifies their surface chemistry, produces tenuous atmospheres and ionospheres, and leads to rings of gas and dust circling Jupiter. These processes are generally harmful to life, but they could also be a major source of energy for possible biota in the oceans of the icy moons. Finally, observations of the charged particle bombardment on the chemistry of the environment is important to studying their habitability. Measurements from JIMO on the electromagnetic induction responses from the moons to Jupiter's rotating field will reveal information about the interiors of the moons, including the presence of liquid sub-ice oceans.

Jupiter System Objective A*: To study interactions among the icy moons' atmospheres, surfaces, interiors, and the magnetosphere.*

1. Investigation: Determine the effects of the Jovian magnetosphere on the icy moons such as the formation of the atmosphere and ionosphere, modifications of the surfaces, creation of gas and dust torii and modifications of the radiation environments of the satellites; the approach is to study the structures, compositions, dynamics and energetics of the interacting system.

Measurements

a. Make continuous field, plasma, energetic charged particles, neutral particles, plasma waves and dust measurements from spiral-in and circular orbits around the moons with the following requirements:

(1) Measure the magnetic field with a sampling of every 0.2 s and a sensitivity of 0.1-nT.

(2) Measure the plasma environment in the energy (E) range of 1- to 50-keV with a resolution of ΔE/E ~ 0.10. For the atomic mass range of H^+ through S^+, a mass (M) resolution of M/ΔM = 10 is required. An angular resolution of ~10° over 4-pi steradians is need with a sampling rate of less than 2 minutes.

(3) Measure energetic charged particles in the energy (E) range of 10-keV to 10's of MeV per nucleon with an energy resolution of ΔE/E ~ 0.3 and an elemental compositional resolution of 10 MeV/nucleon. Observations are needed at a sampling of time of less than 1 minute, with an angular resolution of ~10° over 4-pi steradians.

(4) Measure low energy neutral atoms in the energy (E) range of 10 eV to 1 keV with an energy resolution of ΔE/E ~ 0.3 for elements ranging from H to S with a mass resolution (ΔM) of ~1.

(5) Measure energetic neutral atoms in the energy range (E) of 1- to 150-keV per nucleon with an energy resolution (ΔE/E) of ~0.3. Observations are needed over an angular resolution of at least a few degrees.

(6) Measure the elemental composition, spatial and temporal distribution of dust in the 0.1- to 1-μm size range with a mass (M) resolution of M/ΔM of 2500 or better. Evaluation of the size, charge and velocity of particles in the 0.5- to 100's of km/sec range is needed. Observations needed with an angular resolution of 45°.

(7) Measure radio and plasma waves. Required frequency for electric fields is 1-Hz to 40-Mhz with a frequency (f) resolution of Δf/f = 5% and a sensitivity of 0.l μV/m. An observation rate of 1 spectrum every 5 seconds is required. Magnetic fields need to be measured in the frequency (f) range of 1-Hz to 50-kHz with a resolution of Δf/f = 5%. An observation rate of 1 spectrum every 5 seconds is required. Determine plasma wave wave-normal angles and Poynting flux, and broadband waveform in the range of 1-Hz to 50-kHz; .

(8) Radio plasma sounding in the 1-kHz to 10-Mhz range to determine plasma electron density. Measure local resonance plasma density, profiles of ionospheric density and for subsurface sounding observations evaluate ionospheric corrections up to a frequency of 50-Mhz.

b. Directly sample the major and minor constituents of the neutral atmospheres from circular orbit and "spiral-in" orbit over mass range up to 300 amu, m/Δm of 300, angular resolution: 5x5 degrees^2.

c. Measure emissions and absorption from neutral species in the atmosphere [*e.g.,* O (130.4, 135.6, 630.0 nm), H (121.6 nm), Na (5890.0, 589.6 nm), K (766.5, 769.9 nm)]. Simultaneous multi-wavelength hyper-spectral imaging (UV- IR resolution > 2000; spatial scale 20-km/pixel), with solar/stellar/radio occultations where possible. For spectroscopy of solar

and stellar occultations, wavelength range 50- to 320-nm, spectral resolution >2000, time resolution 1 second or better.

d. Measure emission profiles above the limb to determine altitude profiles of atmospheric composition and temperature at wavelength and resolution requirements as in c above, with altitude resolution ~5 km at the limb.

e. Map the auroral emissions over the surface and above the limb of the satellites for the wavelength range 50- to 320-nm, at a spectral resolution > 2000, and an altitude resolution ~5 km at the limb.

f. Higher temporal, spatial and pitch angle resolution field, plasma, energetic charged particles, neutral particles and dust measurements over specified intervals encompassing wakes, Alfven wings and sharp boundaries to determine the properties and composition of newly added particles with the following requirements:

(1) Measure the magnetic field with a sampling of every 1/60 s and a sensitivity of 0.1-nT.
(2) Measure the plasma environment in the energy (E) range of 1-eV to 50-keV with a resolution of $\Delta E/E \sim 0.10$. For the atomic mass range of H^+ through S^+, a mass (M) resolution of $M/\Delta M > 30$ is required. An angular resolution of ~5° over 4-pi steradians is need with a sampling rate of less than 10 seconds.
(3) Measure energetic charged particles in the energy (E) range of 10-keV to 10's of MeV per nucleon for ion with an energy resolution of $\Delta E/E \sim 0.1$ and an elemental compositional resolution of 10 MeV/nucleon. Observations are needed at a sampling of time of approximately 10 seconds, with an angular resolution of ≤5° over 4-pi steradians.
(4) Measure low energy neutral atoms in the energy (E) range of 1 eV to 1 keV. Evaluate flux and composition for elements ranging from H to Fe. Also, make measurements for simple molecules and isotopes.
(5) Measure energetic neutral atoms in the energy range (E) of 1- to 150-keV per nucleon with an energy resolution ($\Delta E/E$) of ~0.3. Observations are needed over an angular resolution of at least a few degrees and multiple coincidence (e.g. start, stop, and energy) to eliminate penetrating background particles.
(6) Measure the elemental composition, spatial and temporal distribution of dust in the 0.1- to 1-μm size range with a mass (M) resolution of $M/\Delta M$ of 2500 or better. Evaluation of the size, charge and velocity of particles in the 0.5- to 100's of km/sec range is needed. Observations needed with an angular resolution of 45°. Measure the composition of organic and inorganic molecules through ion mass analysis.
(7) Measure plasma waves. Required frequency for electric fields is 1-Hz to 40-Mhz with a frequency (f) resolution of $\Delta f/f = 5\%$ and a sensitivity of 0.1 μV/m. An observation rate of 1 spectrum every 5 seconds is required. Magnetic fields need to be measured in the frequency (f) range of 1-Hz to 50-kHz with a resolution of $\Delta f/f = 5\%$. An observation rate of 1 spectrum every 5 seconds is required. Plasma wave wave-normal angles and Poynting flux in the range of 1-Hz to 50-kHz.. Measure broadband waveform in the range of 1-Hz to 50-kHz And in selectable bands up to 40 MHz. Measure the DC electric field at a rate of 1 measurement per second with a sensitivity of 25-mV/m and a resolution of 5-mV/m.
(8) Radio plasma sounding in the 1-kHz to 10-Mhz range to determine plasma electron

density. Measure local resonance plasma density, profiles of ionspheric density and for subsurface sounding observations evaluate ionospheric corrections up to a frequency of 50-Mhz. Desired guided echo analysis of local field line length and connection to icy satellite ionosphere, and in the “bullseye” spatial distributions of some radiolytic species on trailing hemisphere surfaces of the moons.

2. Investigation: Determine the interior structures of the icy satellites from electromagnetic induction response. Conductors such as salty liquid oceans and metallic cores interact with Jupiter’s rotating field and generate induction fields. Plasma interactions with the moons also perturb the electromagnetic environment. Therefore, comprehensive field and plasma measurements are required to separate the internal and external responses and determine the interior structures of the moons.

Measurements

a. Make continuous field, plasma, energetic charged particles and plasma wave measurements from spiral-in and circular orbits around the moons with the requirements stated in Investigation 1, Measurement a.

3. Investigation: Constrain the effects of particle sputtering on surface frosts, atmospheres and composition of minor constituents of the surfaces of the icy moons.

Measurements

a. Image frosts with a spatial scale of 100-m pixel in infrared, visible and UV bands and relate the observations to direct field and plasma measurements of Investigation 1, Measurement a.

b. Image airglow and satellite aurorae at UV wavelengths with a scale of 1-km/pixel and relate to direct field and plasma measurements of Investigation 1, Measurement a.

c. Perform spectral imaging in the x-ray band at a scale of 100-m/pixel with the following requirements. E range of 0.25 keV to 4 keV (corresponding to k shell fluorescent lines of elements ranging from C to Ca) with a minimum of 10 by 10 image pixels per map element.

d. Directly sample the major and minor constituents of the neutral atmospheres from circular orbit and "spiral-in" orbit over mass range up to 300 amu, $m/\Delta m$ of 300, angular resolution: 5x5 degrees^2**.**

Jupiter System Objective B*: To study the composition, structure, chemistry, and dynamics of Jupiter’s atmosphere to understand the energetics, interaction and evolution of the Jupiter system; understand processes at small space and time scales, in which fundamental chemical and physical processes are occurring.*

1. Investigation: Study atmospheric dynamics at scales ranging from less than one scale height to the planetary scale to understand convective processes and water abundance.

Measurements

a. Measure the dynamics of individual thunderstorms and cloud features over their life cycles at a scale of 10-km/pixel with a sampling rate of 10^3 s. Determine spatial distribution of lightning and convective cells on a global scale at spatial resolution of 10-km/pixel; requires visible and near-IR imaging in a minimum of two broad bands.

b. Measure the water variability at and above the clouds with global coverage at 100-km/pixel, using 5-micron imaging spectroscopy with spectral resolution > 3000.

c. Measure the three-dimensional gaseous ammonia distribution with 5000-km horizontal spatial resolution at 1- to 5-bars and 200-km resolution at 0.01- to 0.5 bars. Passive microwave radiometry at 1- to 5-cm wavelength suggested for 1- to 5-bar region. Mid-IR (10 microns) imaging suggested for 1- to 0.5-bar region; spectral resolution > 2500.

2. Investigation: Study the temperature and energy balance of Jupiter to understand the role of solar insolation, magnetospheric interaction, winds and eddies in atmospheric circulation and convection.

Measurements

a. Measure the poleward eddy heat flux from simultaneous maps of wind and temperature at horizontal scales of 100-km or better at 7- to 8-microns with spectral resolution > 1000 and at 14- to 40-microns with spectral resolution > 50.

b. Obtain global temperature maps, including auroral regions, for vertical temperature structure, waves and horizontal gradients (for deriving thermal wind shears) over a pressure range of 1- to 500-mbar; limb sensing with 20- to 40-km vertical resolution is required for adequate lower stratosphere coverage; same spectral requirements as Measurement a with global coverage and horizontal scale of 20- to 40-km at the limb, 100-km global.

c. Use repeated radio occultations to obtain vertical temperature profiles closely spaced in space (~1000-km) and time (within a few Jupiter rotations) for investigating wave propagation in the thermosphere, stratosphere and upper troposphere.

d. Image Jovian aurora at IR, UV and X-ray wavelengths frequently (over time scales of minutes, hours, days and weeks) while simultaneously making field and plasma measurements in equatorial regions mapping to the aurorae (same field and plasma measurement requirements as in Objective A, Investigation 1, Measurement a).

e. Map atmospheric wind velocities (to 10s of meters per second) as a function of altitude from the tropopause to the thermosphere. Measurement times scales of days to weeks.

3. Investigation: Study Jupiter's clouds, hazes and precipitation, including composition, chemistry and disequilibrium species to understand moist convective processes, vertical structure, atmospheric sources, sinks and dynamics; these studies typically require high spectral resolution.

Measurements

a. Determine global and regional cloud vertical structure (including lightning or convective regions identified from Investigation 1, Measurement a from 0.1- to 5-bars from visible or near-IR imaging; requires simultaneous visible and near IR spectral imaging with comparable spatial resolutions, to identify the locations and composition of the clouds; spectral resolution sufficient to resolve molecular absorption bands (resolution > 300). Middle IR spectral imaging (~8 micron) with spectral resolution > 1000. Far IR imaging with a spectral resolution > 500.

b. Characterize photochemical hazes from ultraviolet imaging, visible wavelength polarization, and infrared mapping (0.3- to 5-microns) at multiple incidence angles within a Jupiter rotation. Spectral resolution ~50 to 500, spatial resolution of 100-km/pixel.

c. Search for NH_3, NH_4SH and H_2O ice signatures with spatial resolution of 10-km/pixel;. requires near-IR through far-IR mapping with spectral resolution of ~20 to 500.

d. Measure the three-dimensional distribution of disequilibrium species, *e.g*., PH_3, CO, using mid- and far-IR wavelengths at 100-km/pixel spatial resolution, spectral resolution > 2000 to 5000 and determine the para H_2 fraction above the visible clouds, by far IR mapping with 100-km/pixel spatial resolution and spectral resolution > 100.

e. Measure the three-dimensional distribution of organic (hydrocarbon) molecules at 100-km/pixel spatial resolution with global coverage, including auroral regions, and spectral resolution > 10000 in the mid-IR (8- to 16-microns); limb spectroscopy with 20- to 40-km vertical spatial resolution (for vertical distribution).

f. Monitor UV (50- to 320-nm, spectral resolution of ~ 1000 to 2000) stellar and solar occultations to obtain high vertical resolution measurements of composition and temperature.

g. Measure spatial distribution of precipitation at 1000-km/pixel spatial resolution at depths of 1- to 5- bars.

Jupiter System Objective C: *To study the structure and dynamics of the Jovian magnetosphere, including processes that generate Jupiter's aurora.*

This investigation supports Objective A, in that understanding the overall Jovian magnetosphere structure and dynamics provides an essential boundary condition to the interactions between the magnetosphere and icy satellites. The magnetosphere is buffeted by the solar wind and is strongly modified by internal processes, such as those associated with Io; however, the relative importance of these perturbations is not understood. Furthermore, processes in the magnetosphere accelerate charged particles to enormous energies that provide the radiation background in which the icy satellites are embedded; these acceleration processes are largely speculative and not well understood. Finally, the magnetosphere and icy satellites are coupled to the Jovian ionosphere and atmosphere through the Jovian magnetic field; evidence for this coupling is found in the Jovian aurora, both magnetospheric and satellite footprints.

1. Investigation: Investigate the structure of the Jovian magnetosphere and its boundaries; determine the relative importance of solar wind and internal drivers in magnetospheric dynamics.

Measurements

a. Make continuous field, plasma, energetic charged particles, neutral particles, plasma waves and dust measurements during transit between icy moons, during Jupiter approach and during transit through the upstream solar wind and magnetosheath with the requirements specified in Objective A, Investigation 1, Measurement a.

b. Image the synchrotron radiation belt at Ka and X band over time scales of hours, days and weeks and relate the images to the field and plasma conditions in the magnetosphere (same field and plasma measurement requirements as in Measurement a above).

2. Investigation: Study the coupling of the icy satellites and magnetosphere to the Jovian ionosphere and atmosphere and the generation of auroras in Jupiter.

Measurements

a. Image the footprints of icy satellites in the Jovian ionosphere with a resolution of 10–km/pixel or better at IR and UV wavelengths while making direct field and plasma measurements in the vicinity of the moons (same field and plasma measurement requirements as in Objective A, Investigation 1, Measurement a).

b. Image Jovian aurora at IR, UV and X-ray wavelengths frequently (over time scales of minutes, hours, days and weeks) and monitor auroral radio emissions continuouslywhile simultaneously making field and plasma measurements in equatorial regions mapping to the aurorae (same field and plasma measurement requirements as in Objective A, Investigation 1, Measurement a).

c. Map atmospheric wind velocities (to 10s of meters per second) as a function of altitude from the tropopause to the thermosphere. Measurement times scales of days to weeks.

Jupiter System Objective D: *To study the interaction of Io and its atmosphere with the Jovian system.*

1. Investigation: Determine the composition of the bound, extended, and escaping atmosphere.

Measurements

a. Make spectroscopic measurements of Io's atmosphere at wavelengths of 0.2- to 0.4-μm with a spectral resolution of 400 and a spatial resolution 100-km/pixel.

2. Investigation: study the relationship of Io's volcanic activity to the structure and dynamics of Io's torus, Io atmospheric auroral emissions, and auroral foot point intensity in Jupiter's atmosphere.

Measurements

a. Obtain frequent global images of Io (minimum 3 colors (violet, green, IR) at 10-km/pixel or better) over a range of temporal scales (e.g. hourly, daily weekly, monthly).

b. Simultaneously (with measurement a) image Io's atmospheric auroral and day glow emissions over the wavelength range of 50- to 400-nm with a spectral resolution of 400 and a spatial scale 100-km/pixel.

c. Simultaneously (with measurement a) image Io's torus at wavelengths 50- to 400-nm and a spatial resolution 0.5 mrad and spectral resolution of 1000.

d. Simultaneously (with measurement a.) image Io's auroral footprint in Jupiter's atmosphere with a resolution of 10-km/pixel or better in at least three different wavelengths in the infrared to UV bands.

e. Make direct continuous field and plasma measurements simultaneously with measurement a. in the outer torus (near Europa's orbit) with the requirements stated in Objective A, Investigation 1, Measurement a, with simultaneous hyperspectral imaging of Io and its torus at wavelengths of 50- to 420-nm and spatial resolution 0.5 mrad or better.

Jupiter System Objective E: *To determine the structure and particle properties of the Jovian ring system.*

1. Investigation: Determine the size distribution in each ring component

Measurements

a. Obtain broad-band images of each ring component at visual to near IR (0.4- to 2-micron) wavelengths and multiple phase angles; include phase angles > 178° and < 5°; phase angle sampling < 10°; signal-to-noise > 100. Spatial resolution < 10-km/pixel; field of view > 10,000-km.

b. Obtain visual to IR (0.5- to 5-micron) spectral image cubes of each ring component. Signal-to-noise > 100; spectral resolution < 0.02 microns; spatial resolution < 50-km/pixel; field of view > 15,000-km, for at least 5 phase angles including < 10° and > 175°.

c. Obtain far IR emission spectra of the main ring; signal-to-noise > 100; wavelength range 5- to 300-microns.

2. Investigation: Determine the three-dimensional structure of the Jovian ring system.

Measurements

a. Obtain edge-on images of the entire ring system at 10-km/pixel spatial scale; multiple (> 5) phase angles including < 10° and > 170°; several visual and near-IR wavelengths; multiple longitudes relative to the nodes of Amalthea's and Thebe's orbits to search for orbital concentrations.

b. Obtain broad-band images of the halo crossing into the Jovian shadow, as viewed from within the shadow; multiple broadband filters in the visual and near-IR; resolution < 10-km/pixel; field of view > 10,000-km.

c. Obtain high resolution (10-km/pixel spatial scale) images of the main ring at multiple (> 5) phase angles including < 10° and > 175° and several visual and near-IR wavelengths.

3. Investigation: Determine the composition of the rings and embedded moons.

Measurements

a. Obtain visual to IR (0.5- to 5-micron) spectral image cubes of Adrastea, Metis, Amalthea and Thebe at a spectral resolution 0.02 microns, phase angle < 20° and for multiple rotational phases.

b. Obtain visual to IR (0.5- to 5-micron) spectral image cubes of each ring component with a signal-to-noise > 100, spectral resolution < 0.02 microns, phase angle < 20°, spatial resolution < 10-km/pixel, and field of view > 15,000-km.

4. Investigation: Complete a comprehensive search for small inner moons of Jupiter, down to a size of 100-m, and study time-variations in the Jovian ring system.

Measurement

a. Obtain broad-band visual imaging at low phase angles, using long exposures to achieve needed sensitivities; make repeated observations over >1-2 years to obtain well-defined orbits and long time base.

4.0 MISSION AND SPACECRAFT CAPABILITY AND REQUIREMENTS

4.1 Space system

The conceptual JIMO space system derived by a government study team led by the Jet Propulsion Laboratory with participation by other NASA centers and the Department of Energy. for its Technical Baseline 1 (TB1) has provided the context for SDT considerations about the feasible science on the JIMO mission. The SDT recognizes that this early design concept is neither optimal nor final and that further work is ongoing.

The key characteristics of the JIMO space system (Appendix 4) include a nuclear fission reactor power source providing over 100 kW of continuous power; ion-drive electric propulsion system producing at least 35 km/s of delta-V allowing escape from Earth, insertion into Jupiter orbit, and insertion into high-inclination, low-altitude orbit about each of Jupiter's icy satellites in turn; a dedicated radiation-hardened RAD 750-class science computer; and a data rate of ~10 Mbps from Jupiter via a steerable high-gain antenna that allows simultaneous science observing and data downlinking. The telecom system includes an Ultra-Stable Oscillator (USO) needed to support radio science investigations. The space system will be 3-axis stabilized and will operate in the nadir-oriented, gravity-gradient attitude during satellite low-orbit phases.

4.1.1 Mission module

The JIMO mission module will include all the science instruments plus their associated software and any required support structure such as a scan platform, a turntable, mounting booms, and any auxiliary payloads that may be deployed from the main JIMO space system.

The Project's TB1 concept includes a high-precision pointing scan platform that carries several boresight-aligned remote sensing instruments. The scan platform allows both clear nadir and limb viewing when in low orbit and distant observations in other directions during transitions between satellites to view targets such as Io. The scan platform is designed to keep the instruments within the reactor radiation shield cone and positioned above the plane of the ion thrusters. Provision is made for a possible thermal radiator to have a wide view of deep space.

The TB1 design also includes a continuously rotating turntable on a boom extending from the main space system bus. Instruments mounted on this turntable will have at least a hemispheric clear view of space including the orbital velocity ram direction. The rotating actuator will include a provision for transferring commands and data across the interface, with the instruments remaining within the radiation shield cone and above the thruster plane.

Provision is made for mounting other science instruments directly onto the bus. Such instruments can also view in the nadir direction but might have less stringent pointing accuracy requirements than those on the scan platform or might be too massive to be accommodated on the platform. Room can be made on the bus for mounting an auxiliary payload, its release mechanism, and any telecomm equipment need to support such a payload after its deployment.

The expected radiation dose from the Jovian environment and from the reactor at the location of the mission module (inside the radiation shield cone) for the TB1 baseline is severe and presents difficult challenges for science instrumentation. The SDT recommends that the JIMO Project provide space inside shared shielded vaults for instrument electronics that need additional shielding. Such vaults should be provided within the bus, on the scan platform, and on the turntable, as required. The AO should also include a menu of radiation-hardened parts that can be procured through the Project or from its specified vendors by instrument developers.

4.1.2 Payload Accommodation Envelope

The JIMO Project presented a draft Payload Accommodation Envelope (PAE) to the SDT for its assessment at its September 2003 meeting. Since that time, there have been several discussions between the SDT and JIMO Project engineers to try to reconcile the PAE with the capabilities that the SDT envisions will be needed to meet its measurement requirements. The current version of the PAE, which is still in work, is shown in Table 4-1. Pink-colored entries are still being evaluated for formal adoption by the Project. The SDT evaluation of the various PAE capabilities are color coded in the Table – green indicates that the planned capability is acceptable, yellow that it is still TDB, orange that it is partially unacceptable, and red that it is unacceptable. While in most respects, the JIMO space system appears to provide an excellent basis for making the scientific measurements required to meet the SDT's objectives, some of the provisions of this proposed payload accommodation envelope appear inadequate to the SDT. Of primary concern is the volume allocation for body-mounted instruments. The scan platform pointing jitter capability is still TBD, but the SDT is concerned that it may be several factors away from what is likely required to support the SDT baseline measurement objectives. The SDT is also concerned that limitations on the processing capability of the science computer may force the high-rate instruments to do data preprocessing in dedicated instrument-provided processors, which would be expensive and difficult to radiation harden. The AO will need to make clear what the real limitations are for onboard data processing in the science computer.

The Project has indicated to the SDT that use of plutonium-fueled RTGs or RHUs on the JIMO space system is to be avoided, if at all possible. The SDT is concerned that such a proscription will make Europa Surface Science Package infeasible. The AO should make it clear whether or not the use of such power sources can be considered. Other PAE elements needing further Project work include provisions for shared cooling resources for the payload, orbit stability and control capabilities, and the expected levels of non-gravitational disturbances.

4.1.3 Optical Communication

Improved communications technology is of obvious benefit to future exploration mission. Optical communications is only one of several major improvements in the interplanetary net being studied at the current time. However, a technology demonstration optical technology experiment on JIMO would be useful to JIMO science goals only if it could be used effectively operationally, implying challenges in radiation hardening, mission design and development of the ground infrastructure. Given the complexity and scale of such an experiment the SDT does not recommend including this in the Payload Accommodation Envelope. We do encourage the project to explore cost-effective, low mission impact ways of potentially increasing data rates above the current PAE value of 10 Mbps. One possibility is to design the communication formats, data handling software and bus architecture to be able to handle higher data rates (~100 Mbps or greater), so that potential improvements in future DSN capabilities can be used with the baseline JIMO communication system if they become available.

Table 4.1. JIMO Proposed Payload Accommodation Envelope – Part 1

Item	Total	Bus Mounted	Scan Platform	Turntable	Aux Payload	SDT Evaluation
No. of instruments	18				1	OK
Payload Mass	1500 kg total (includes instruments, platforms, antennas, etc.)	1500 kg	Instruments </=TBD kg	Instruments </=TBD kg	375 kg	OK
Footprint		3 m^2	2 m^2	1 m^2	1.2 m dia x 1.7 m length	OK, keep in mind necessity for coolers
Volume		1.5 m^3	1 m^3	0.75 m^3	1 m^3	OK except for bus-mounted payload, which is likely too small to support one or more high-capability instruments
Field of Regard		<2 π steradian, centered on nadir, except for TBD objects in field-of-view at TBD locations	Hemisphere, except ion engine pods, boom(s), & antennae(s)? in field-of-view at TBD locations . Able to view bus-mounted cal targets.	Hemisphere centered ~90 deg from nadir plus pi sr in other hemisphere centered >60 deg from nadir (not necessarily on turntable), except boom(s) in field-of-view at TBD locations		OK
Unique structures / interfaces		</=4 booms (two </=10 m in length, one </=15m plus long dipole antenna 30m tip to tip) in TBD orientation(s)			S/C to provide interfaces only (release mechanism provided by Aux. Payload)	OK
Thermal		-20 to +50 deg C at interface, incident thermal radiation from S/C </=0.1 W/cm^2, instruments provide replacement heaters as needed				OK
Power	>10 kW when not thrusting, </=3 kW when thrusting	TBD	TBD	TBD	TBD	OK
Telecommunications Support					None (provided by the payload)	OK
Space System Pointing (control)		20 mrad, mounting plane perpendicular to nadir direction			20 mrad	OK
Instrument Platform Pointing (control)			1 mrad, gimbaled about 2 orthogonal axes in the plane perpendicular to nadir direction	20 mrad, spin axis perpendicular to velocity vector		OK
Space System Pointing (knowledge)		0.1 mrad			0.1 mrad	OK
Instrument Platform Pointing (knowledge)			0.1 mrad	0.1 mrad		OK
Slew / turn rates			Slew rate </=40 mrad/s, </=TBD µrad jitter	Turn rate ~3 RPM		Slew rate OK. Jitter should be <50 µrad/s (or amplitude <10 µrad) for science floor; <1µrad/s (or amplitude <2.5 µrad) for baseline
Sun avoidance		None	Mission Module S/W avoids sun pointing	None	None	OK

Table 4.1. JIMO Proposed Payload Accommodation Envelope – Part 2

Item	Envelope	SDT Evaluation
Spacecraft orientation	In Science Orbit: gravity gradient stabilized attitude, Mission Module nadir-pointed; off-nadir orientation up to +/-20 degrees for </= 10 minutes at a time. In other Jupiter phases: thrust vector in any direction, roll orientation constraints TBD.	OK
Instruments on high voltage bus	</=2	OK
Orbit reconstruction	1 m radial, 10 m cross track, 100 m along track	OK
Environmental	TBD, goal to achieve Cassini levels in science orbits	TBD
Contamination by thruster exhaust	No direct plume impingement. Contamination control plan. Some instruments may need covers and/or heaters	OK
Checkouts / calibrations	Using external sources (celestial, cal target, etc.) - every 6 months during cruise and every month in Jupiter orbit. Using instrument internal sources - every 2 weeks during cruise and every week in Jupiter orbit. Radio science at near-Earth opposition. Weekly USO frequency monitoring.	OK
Maximum Data Rate Input to Science Computer (total for all instruments)	Maximum aggregate data rate 600 Mbps. Maximum output rate across any single instrument interface </= 80 Mbps. Multiple interfaces from a single instrument are possible. No limit on number of instruments operating simultaneously	OK
Data Rate - Downlink (science & engineering)	10 Mbps	SDT to assess need for 20 - 50 Mbps; surely need no less than 10 Mbps at 6.2 AU
Max daily science D/L volume	500 Gb (science orbit)	SDT to assess necessary data volume
	150 Gb (outside low orbit)	SDT to assess expected need for higher data volume during transitions between satellites
Data Storage	500 Gb	May not be adequate pending possible changes to data downlink rate or volume requirements
Science Computer	RAD 750	May need two of these
Data processing or compression by Spacecraft Computer	None (packetization and framing only)	OK
Data interface to Science Computer	1553, 1394, ~~or LVDS~~	OK
RHUs/RTGs	Discouraged; maybe precluded?	Will Project allow them on landed science package?
Target motion compensation	Cassini-level capability	OK
Shielded vaults for instrument electronics	Space for up to 20 6U cards or equivalent.	OK
Dissipation of thermal load from each instrument	?	Require clear view of cold space (?); investigate thermal dissipation by S/C and shared active cooling
Maneuver durations	<4 hours to complete each momentum management or satellite orbit maintenance maneuver	OK but strongly desire <<4 hr
Spacecraft USO	USO frequency reference for both Ka and X band with Allan deviation <10^-13 over 1000 sec.	OK
Satellite orbit characteristics	Goal is to accommodate: Inclination: >/=70° Eccentricity: starting value near circular (<0.1) Altitude: 100 – 500 km Phase angle at orbit node: 30° to 70° Change of nodal phase by >10 deg during satellite stay. Orbital stability and planetary protection TBD.	?
Duration in low satellite orbit	Current baseline of 30 days at Europa, 120 days at Ganymede, and 120 days at Callisto.	Meets science floor, but baseline mission should have 60 days at Europa.
Non-gravitational disturbances in satellite orbit	Goal is to minimize frequency and magnitude of thruster events. Reaction wheel momentum dumps <once/day and using balanced thruster couples. Thruster events planned only when S/C is being tracked, if possible. Reactor radiator configuration to produce minimium torques on the S/C from atmospheric drag. Capability is TBD.	?
Satellite orbit control and change capability	?	?
Observations between satellites	Able to perform science observations during transit between satellites	OK

4.2 Mission Duration and Orbits

The SDT has determined that the highest priority JIMO science objectives can only be satisfied if the space system spends adequate time in suitable orbits close to the Jovian icy satellites. The typical orbit required to satisfy the majority of the JIMO scientific investigations has the following characteristics:

Inclination:	≥70°
Eccentricity:	starting value near circular <0.1*
Altitude:	100 – 500 km
Phase angle at orbit node:	30° to 70°

*Note: studies conducted subsequent to the Mission Science Workshop indicate that stable orbit cannot be achieved with eccentricities as small as that recommended in Appendix 2, therefore a lager value is reflected in this table

Because of the inherent instability of such orbits (see Sec. 4.6), the SDT recognizes that repeated propulsive orbit adjustments will likely be necessary to satisfy mission safety requirements. A robust backup (small chemical propulsion system) might be required in addition to the ion thrusters. Orbit control maneuvers will need to be carried out in such a way as to not seriously degrade the ability to reconstruct the space system orbit during the satellite gravity determination phases.

The period of time in the above-described science observation orbit at each satellite required to meet the SDT science objectives is:

	Science floor	*Planning Baseline*
Europa	30 days	60 days
Ganymede	60 days	120 days
Callisto	60 days	120 days

The science floor duration is set by the minimum time required to provide overlapping remote sensing orbit tracks for dual global coverage of each object from 100-km altitude at emission angles <45°. A second requirement is to measure the satellite's tidal response signatures over a period of four satellite orbital periods about Jupiter; this requirement is consistent with the global mapping requirement. Dual global coverage will allow science investigations that 1) obtain both high- and low-phase remote sensing observations, 2) accomplish very high-resolution observations of selected targets, 3) achieve geophysical coverage (*e.g.*, radar, gravity, sounding, laser altimetry), and 4) conduct comprehensive particle and fields investigations.

The mission planning baseline durations provide a factor of two margin in time for achieving the science objectives to account for probable requirements for time sharing of investigation types, downlink strategies, and multiple orbit phases (*e.g.,* high and low altitudes) as well as robustness against operational anomalies.

The SDT estimates that during the gravity and altimetry investigation periods, the space system orbit will need to be reconstructed to an accuracy of ±1 m in the radial direction over periods of at least 3 satellite orbits about Jupiter. Errors in reconstructing the spacecraft altitude will map directly into errors in measuring the amplitude of the eccentricity tidal potential and thereby degrade our confidence in determining the presence of a subsurface ocean.

While the SDT fully expects that remote sensing and *in situ* particles and fields measurements will be obtained while transitioning from one satellite to another, it places no requirements on the orbital characteristics during these periods.

4.3 Mission summary

As for the space system, the conceptual JIMO mission derived by the government study team for its Technical Baseline 1 (TB1) has provided the context for SDT considerations about the science that might be feasible on the JIMO mission.

The TB1 mission is launched in 2012 with a flight time to Jupiter in the range of 5- to 8-years and a stay time in the Jupiter system of an additional 4- to 6-years (see Appendix 4). The space system is inserted into orbit around each of the Jovian icy satellites in turn using the ion thrusters to spiral in to a low circular orbit and to spiral back out again and to maneuver to the next satellite using satellite gravity assists along the way.

Figure 4-1 shows a representative timeline for transitioning between Ganymede and Europa. We observe that during the majority of time required to transition from Ganymede to Callisto (or Callisto to Ganymede) the ion thrusters are not being used; this provides substantial time for "clean" remote sensing of Jupiter system targets and particles and fields measurements during these phases. We anticipate continuous low-rate particles and fields science and a duty cycle of ~20% for selected high-rate remote-sensing science when the thrusters are off. The current plan calls for 1- to 2-DSN passes per day to downlink the data during these phases. The SDT recommends that DSN coverage during transit between satellites be commensurate with that during operations at each moon.

The baseline orbital altitude about the icy satellites for the TB1 mission is 100 km. At this altitude the orbital period is about 125 min at Europa and about 150 min at Ganymede and Callisto. The Earth and Sun will be occulted for about 40% of each orbital period, and a Jupiter occultation occurs each satellite orbital period about Jupiter (the duration in Jupiter occultation is ~3 hours for Europa, ~4 for Ganymede, and ~5 for Callisto). Nearly continuous DSN coverage is planned during the satellite low-orbit phases. Orbit control is not expected to be unduly obtrusive during these phases with maneuvers anticipated less often than once per day.

Continuous measurements by the active remote sensing and fields and particles instruments are expected during the satellite low-orbit phases. Remote sensing instruments that measure reflected sunlight will likely operate continuously on the day side of each orbit, while those that measure temperature will operate on the day and night sides. Data will be stored onboard as necessary and downlinked each orbit during the periods outside of Earth occultation.

The mission will be concluded by placing the space system in an appropriate planetary-protection orbit. Although, analyses are ongoing to determine an appropriate planetary protection orbit, the SDT recommends that the capability to continue science operations from the orbit be retained, if the spacecraft systems are still operational. It is also recognized that such science activity would most likely be part of an extended mission phase. Use of critical science assets once they are in place is an important part of NASA's exploration strategy. JIMO planning should allow for the possibility that the spacecraft may be capable of returning high value science data far beyond its nominal prime mission, and should plan for timely assessments of potential extended operations so they can be proposed and evaluated by NASA

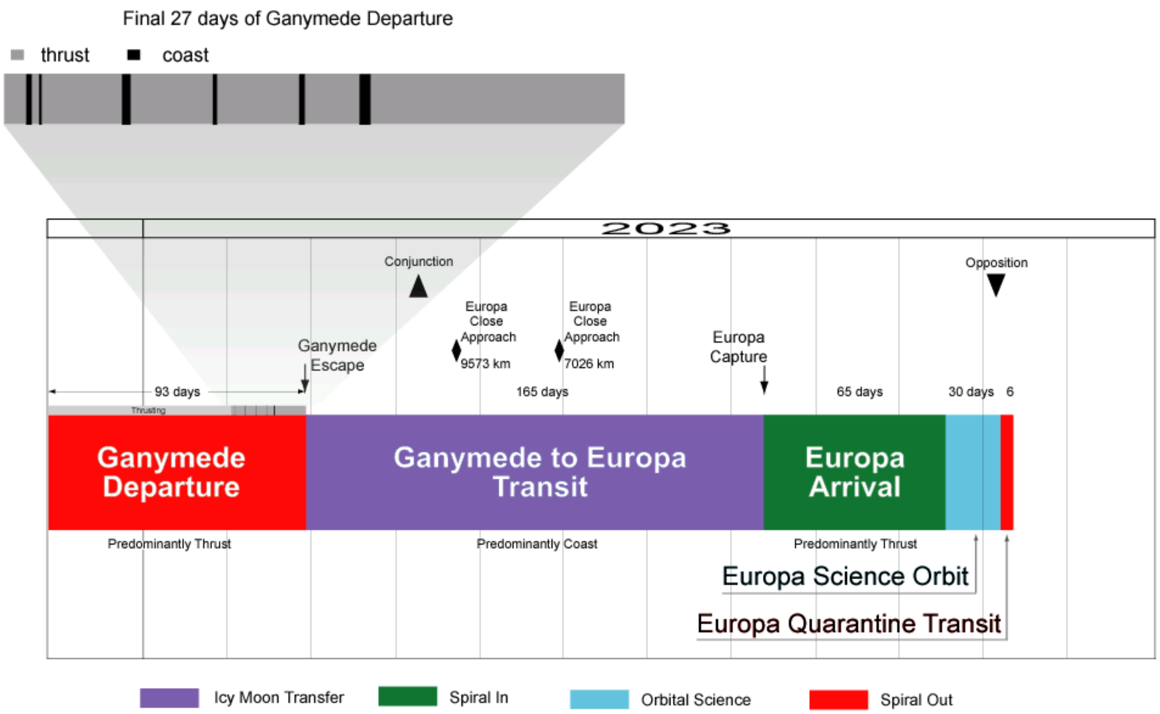

Figure 4.1. Typical Timeline for Transitioning between Satellites

4.4 Interplanetary Cruise science

The SDT recommends that science operations during cruise from Earth to Jupiter be included in the mission profile. Cruise science can include, but not be limited to measurements of the solar wind and targets of opportunities such as asteroids. One of the magnetospheric investigations (dealing with the relative importance of solar wind input to Jovian magnetospheric dynamics) requires *in situ* measurements of the solar wind upon approach to Jupiter while remotely monitoring auroral emissions from the planet. Additionally, many of the instruments will either require or benefit from early calibrations using stars or other targets.

It is important to note that the cruise science is beneficial in many ways that exceed the importance of the observations themselves. Briefly, these benefits include:

a. Provides operational experience for the engineering and flight team that will lead to more efficient science planning for the primary mission at Jupiter**.**

b. Allows the science teams to characterize idiosyncrasies of the performance of their instruments in the environment of the spacecraft.

c. Provides science data and calibrations that enable the science teams to develop and perfect data processing software and calibration algorithms so that valuable time during the prime mission is available for prime mission science.

d. Provides pathfinder data sets for developing archive formats and procedures and allows the science teams to develop and exercise their interfaces with the Planetary Data System well before the prime mission data begins to flow at full speed.

e. Experience with Galileo and Cassini shows that cruise science results generate substantial public interest and provide opportunities to demonstrate the excitement of the prime mission in spite of the very long cruise phase.

The SDT believes that an investment in cruise science significantly increases the efficiency of obtaining science from the prime mission and more than pays for itself over the lifecycle of the mission.

4.5 Mission and space system options

While the baseline TB1 mission design appears to meet the majority of the SDT's science requirements, we are also interested in some possible alternatives. Special orbits for unique science should be considered. These include passes at very low altitudes (<<100 km) in orbits that are very long-lived (inclinations <50°), possibly highly eccentric, or single unbound flybys. Other such orbits will require strategies involving plane changes (inclination and/or phase angles). Use of variable orbit altitudes about the satellites may also be of interest. The SDT recommends that the Project study the feasibility and costs of such alternative mission scenarios. These should incorporate a strategy that minimizes as much as possible the total radiation exposure along with assessing and understanding the range of expected radiation exposure.

The SDT also believes that it is important to understand the potential benefits of orbiting the satellites in a different order (*e.g.*, Europa, then Ganymede, then Callisto) in terms of radiation exposure and ease of achieving a planetary-protection safe orbit.

The ability to control the space-system orbit so as to repeat an orbital pass in all three dimensions needs to be studied. For example, such orbit control to sufficient accuracy is required to make interferometric SAR measurements feasible.

The SDT has discussed various types of auxiliary payloads including surface science packages, penetrators, atmospheric probes, and subsatellites. The consensus view of the SDT is that a Europa surface package needs to be part of the JIMO mission baseline. The space system accommodation implications for supporting this surface package need to be better understood. Areas of concern include mounting the package to the bus, its release mechanism and procedure, use of RHUs and/or RTGs to supply power and thermal control, radiation shielding, and provision for a steerable telecommunications antenna and receiver on the bus. The operational implications of including a surface mission (e.g., landing site selection, delivery accuracy, main space-system orbital requirements for release and telecommunications) will also need study.

The SDT finds that it is crucial that the JIMO space system be electromagnetically clean enough (*Cassini* levels or better) to allow high-precision electromagnetic field measurements and that it not be subject to non-gravitational perturbations or oscillations that degrade the accuracy of the orbit reconstruction and thus the gravity field and altimetry measurements. If these requirements cannot be met with the main JIMO space system, the SDT believes that the priority-one science objectives can only be met by deploying subsatellites in orbit about the icy satellites. This variation of the baseline JIMO approach would have major implications for the design and operation of the mission and the main space system. It is thus, imperative that the ability of the main space system to meet the electromagnetic cleanliness and orbit reconstruction accuracy requirements be firmly established at the earliest possible time.

The SDT believes that a set of calibration targets that can be viewed by the scan platform remote sensing instruments could be highly desirable. We recommend that the AO solicit from proposers what their requirements are for onboard calibration targets, listing separately their associated mass and power, with the understanding that instruments with similar target requirements might be able to share a common target.

4.6 Orbit characteristics

One of the important orbit characteristics for assessing science feasibility for global mapping is the ground track spacing. For orbital altitudes in the range of interest for JIMO (periapsis between 100 – 200 km and eccentricity <0.1), the ground track spacing at Europa is about 9° of longitude at the equator (or about 250 km)/orbit. With this spacing, about 40 orbits would be required to give global surface mapping using just the sunlit side if the instrument fields of view (FOVs) were sufficiently wide to cover 250 km on the surface from an altitude of 100 km. In practice, emission angle and FOV constraints are likely to restrict coverage to swaths no wider than ~70 km. Thus, it will probably take 4 Eurosols (14 days) to achieve one complete global map. Ground tracks over these 4 Eurosols must be precisely interleaved to provide gap-free coverage; this leads to a requirement for an orbital period that is one of a set of discrete values that yield the proper ground track offsets from orbit to orbit. For Europa, the allowed periapsis altitudes for a 4-Eurosol map are spaced about 15 km apart in the range of 100 – 200 km for a given eccentricity, and the orbital period must be maintained to within ~1 sec accuracy over the 4 Eurosols to achieve the desired uniform ground track spacing.

Ground track spacing between successive orbits at Ganymede is again around 250 km, and 4 Ganymedian days (28 Earth days) are required to obtain complete global coverage. Acceptable periapsis altitudes are spaced about 14 km apart. At Callisto, the ground track spacing is about 100 km, so the global map can be completed in only 2 Callistan days (33 Earth days). Acceptable periapsis altitudes are spaced about every 11 km.

While studies are far from complete, assessments to date of the stability of near-circular, low-altitude orbits about the Jovian icy satellites indicate that such orbits are inherently unstable. This instability leads to surface impact on a time scale that depends on inclination, initial eccentricity, initial altitude, and the argument of periapsis. A study using an estimated third-order gravity field for Europa based on *Galileo* measurements showed that orbits are unstable on time scales of days to weeks depending on the initial conditions. However, metastable equilibrium points have been identified for polar orbits having a specific eccentricity (~0.03) and argument of periapsis (90°) for a semimajor axis in the JIMO range of interest. So with occasional orbit corrections, high-inclination orbits appear to be feasible for the science observing phase.

These types of orbits also exhibit a natural shifting of their ascending node positions with time at a rate that depends on inclination, altitude, and eccentricity. These natural nodal regression rates will help to provide the desired different phase angles for remote sensing mapping and gravity determination at reduced or no delta-V cost. They may also lead to preferred orbit inclination angles.

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APPENDIX 1: JIMO SCIENCE DEFINITION TEAM (SDT)

SDT Members	Affiliations
Ronald Greeley (Co-chair)	*Arizona State University*
Torrence Johnson (Co-chair)	*Jet Propulsion Laboratory*
David Senske (Exec. Sec.)	*Jet Propulsion Laboratory*
John Baross	*University of Washington*
Diana Blaney	*Jet Propulsion Laboratory*
Don Blankenship	*University of Texas, Austin*
Bruce Campbell	*National Air and Space Museum*
Robin Canup	*Southwest Research Institute*
Jack Connerney	*Goddard Space Flight Center*
John Cooper	*Goddard Space Flight Center*
John Delaney	*University of Washington*
Hajo Eicken	*University of Alaska*
Paul Geissler	*United State Geological Survey*
Andy Ingersoll	*California Institute of Technology*
Krishan Khurana	*University of California, Los Angeles*
William Kurth	*University of Iowa*
Nick Makris	*Massachusetts Institute of Technology*
Tom McCord	*University of Hawaii*
Chris McKay	*Ames Research Center*
William McKinnon	*Washington University*
William Moore	*University of California, Los Angeles*
Susanne Neuer	*Arizona State University*
Bob Pappalardo	*University of Colorado*
Louise Prockter	*Applied Physics Laboratory*
Bill Sandel	*University of Arizona*
David Sandwell	*University of California, San Diego*
Paul Schenk	*Lunar and Planetary Institute*
Gerald Schubert	*University of California, Los Angeles*
Amy Simon-Miller	*Goddard Space Flight Center*
Larry Soderblom	*United State Geological Survey*
Mitch Sogin	*Marine Biology Laboratory*
John Spencer	*Lowell Observatory*
David Stevenson	*California Institute of Technology*
Peter Thomas	*Cornell University*
Hunter Waite	*University of Michigan*
David Warmflash	*Johnson Space Center*
Dale Winebrenner	*University of Washington*
Maria Zuber	*Massachusetts Institute of Technology*

Ex Officio Members	Affiliations
Orlando Figueroa	*Solar System Exploration Division Director, NASA Headquarters*
Ray Taylor	*JIMO Program Executive, NASA Headquarters*
Michael Meyer	*NASA Headquarters*
John Rummel	*Planetary Protection, NASA Headquarters*
Curt Niebur	*JIMO Program Scientist, NASA Headquarters*
Francesco Bordi	*NASA Headquarters*
Al Newhouse	*Project Prometheus Program Director, NASA Headquarters*

APPENDIX 2: WORKSHOP REPORTS

JIMO MISSION ACCOMMODATION WORKSHOP REPORT

Held at JPL, 14-15 August 2003

L. A. Soderblom, T. V. Johnson, D. Senske (Chairs)

I. Satellite Orbital Observation Periods

	Science Floor	Mission Planning Baseline
Europa	30 days	60 days
Ganymede	60 days	120 days
Callisto	60 days	120 days

Rationale for Science Floor: Minimum required times to provide overlapping remote sensing orbit tracks for single global coverage of each object from 100 km altitude and emission angles <45° is ~15 days, 30 days, and 30 days for Europa, Ganymede and Callisto. The minimum times required for tidal signatures is ~4 X the satellites' orbital periods, consistent with the remote sensing time scales. Additional assumptions were that all experiments operate simultaneously and some multiple looks are required for many investigations. For example at least two complete sets of coverage are required to provide 1) high-phase and low-phase observations, 2) high-resolution targeting, 3) geophysical coverage (radar, gravity, sounding, laser altimetry), and 4) particle and fields investigations.

Recommended mission planning baseline*:* Provides a factor of two margin in the time for achieving objectives to account for probable requirements for time sharing of investigation types, downlink strategies, and multiple orbit phases (e.g. high and low altitudes) as well as robustness against operational anomalies.

II. Observation Orbit Characteristics

A. Typical orbit to satisfy the majority of the scientific investigations:

- inclination ≥ 70°
- eccentricity: starting value near circular (~0.001)
- altitudes 100-500 km
- phase angles 30° to 70°

This requires a mission design that employs a strategy in which orbital stability and lifetime are managed. For example the above orbit could have a lifetime (time to surface impact) of ~50 days with no orbit adjustment. The spacecraft orbit would be propulsively corrected (possibly using the NEP system) with sufficient frequency to satisfy mission safety requirements. A robust backup (small chemical system) might be required in addition.

B. Special orbits for unique science should also be considered. These include S/C passes from very low altitude <<100 km that are either very long-lived (inclinations <50°), possibly highly eccentric, or single unbound flybys. Use of such orbits will require strategies wherein orbital plane changes are accomplished (inclination and/or phase angles) at high altitudes (perhaps 10K-100K km) before or after propulsively spiraling in to science observing altitudes.

C. We also recommend that the JIMO SDT sponsor an additional workshop on spacecraft accommodation of science instrumentation. It was clear from many of our discussions that many currently open issues related to conflicts of field of view, radiators, scan platform(s), need to be explored and elucidated to provide input for preparation of an AO. This could take the form of a short meeting to assess in detail the Payload Accommodation Envelope which will be discussed at the September 2003 SDT meeting.

JIMO Mission Accommodation Issues/Questions

The following are issues for mission and science studies to support the JIMO Science Definition Team. They are listed in priority order based on the Workshop participants' view of their potential impact on key science objectives. Some are more difficult and wide ranging than others and may require extensive study in the future. It is not our intent to require that these items be worked in strict chronological order by priority, but to use the priorities to guide Project mission design activities. We would like to have a status on these items reported at the next SDT meeting, along with thoughts and recommendations from the mission design team on how they plan future work to answer some of the longer-range questions.

0. Confirm viability of maintaining high inclination orbits propulsively
1. Parameterization of time and propellant resources needed to change key orbit characteristics, including:
    a. Delta-v for altitude changes
    b. Delta-v for inclination changes as a f(alt., t)
2. Planetary Protection Strategies Assessment
    a. LONG TERM STABILITY @ EUROPA (>~100 yr) – atmospheric drag effects
    b. Leave Europa – possible orders of encounters to be explored – *italics indicate target for final planetary protection location/impact*
        i. C-G-E-*JUPITER (expected to be difficult)*
        ii. C-G-E-*LEAVE SYSTEM (not likely but needed for completeness)*
        iii. C-G-E-*G* and/or *C*
        iv. C-G-E-*I (time and radiation issues)*
        v. E-G-*C*
        vi. E-G-C-*stable orbit beyond C?*
3. Frequency of required thrusting during science orbits and effect on Orbit Determination and gravity measurements:
    a. To maintain orbit at high inclinations
    b. To control orbit for ground track spacing
4. Orbit Determination accuracy assessment (related to 3) (expected to require a relatively long-term study and assessments during design)
    a. Orbit accuracy in radial direction ~1meter
    b. Revisit Europa Orbiter study of k2 and h2 determination vs time in orbit
    c. Determine error sources and characteristics for JIMO spacecraft/tracking

5. High-order gravity terms effects on orbit stability
    a. Assess current upper limits from Galileo
    b. Incorporate theoretical modeling of ‘worst-case’ interior structures as appropriate (e.g. UCLA work – Bill Moore, SDT)
6. Assess ability to control orbit for repeat-pass In-SAR
    a. Requires ‘re-flying’ a previous orbit track segment (for ~400 km) to within 1-2 km accuracies
7. What is fastest/lowest radiation path to Europa?
    a. Assess as starting point for mission options starting with Europa , compared to current C-G-E order (related to Planetary Protection strategies, #2)
8. How LOW can you go? Assess strategies for very low (<~50km) operations:
    a. Flybys
    b. Low circular orbits
    c. Hi eccentricity orbits
9. Assess typical times to transfer between satellites and typical fraction of this time spent thrusting (mostly complete at required level of detail).

JIMO AUXILIARY SCIENCE PACKAGES WORKSHOP REPORT
Held at NASA Ames, August 2003
Chris McKay (Chair)

Summary: The workshop identified three key science objectives that appear to require the use of auxiliary packages. These are

1) Seismic measurements on Europa and the other icy moons
2) Determination of signs of life in organic material on Europa
3) Measurement of the elemental composition, in particular oxygen abundance, and thermal structure of Jupiter's deep atmosphere.

Seismic measurements on Europa could be key to determining the thickness of the ice shell, the depth of the ocean, and the level of seismicity. This could be achieved on a penetrator or a surface package. Determination that organic material that may be present on the surface of Europa as a result of biological activity will require detailed measurements on a sample of surface material either on the surface by a lander or with material ejected into the path of the orbiter by a dumb impactor. In either case careful targeting of young surface units will be necessary due to radiation processing of organics. Although there have been previous studies of penetrators and landers, for a JIMO application there would need to be significant technology development in several areas including: power, thrust for deorbiting and impact, landing, planetary protection, survival at high radiation and low temperature. For an Astrobiology lander there are additional technology issues with targeting and sample acquisition. A Jupiter Probe that reaches 50 to 100 bars pressure would allow direct measurements of the deep thermal structure and elemental composition. For a Jupiter Probe the question of the availability of the Galileo heat shield material is key to a low-cost development of a heat shield.

1. Geophysics Lander

NB: We have separately considered a Geophysics Lander and an Astrobiology Lander even though there would most likely be some overlap in any actual package. This separation emerged at the workshop as a more natural division than penetrators and landers. Combining both into one category was also not optimal due to significant differences.

Science

The main science that could be achieved by a Geophysics Lander would be seismic measurement. A seismometer on a single lander could address level 1 science objectives dealing with 1) the thickness of the ice, 2) the depth of the ocean, 3) the presence of change (seismicity). These would all be very difficult to get unambiguously from remote sensing.

Having more than one seismometer on the surface would add to the science obtained by giving information on the location of sources and, if natural sources were large enough, giving information on the nature of the interior. But more than one seismic station would not enable further level 1 science objectives. Similarly, an active seismic experiment, in which a dumb impactor is released after the seismic lander, would add to the effectiveness of a seismic lander but would not enable further level 1 science objectives.

Additional science objectives that could be addressed by a Geophysical Lander include surface properties and thermal measurements.

Technology Readiness

Many components of a seismic lander, eg. the seismometer, could be based on mature designs and even flight hardware. Here we just list those aspects that are not mature technology because these are the components that will determine the overall readiness state of the system. These key areas in which there is currently low technology readiness are:

1. Planetary protection: there will almost certainly be severe requirements for sterilization of any packages that land on the surface of Europa, especially ones that carry RTGs or RHUs.
2. DeltaV: from the orbiter it would be necessary for the lander to deorbit and then maneuver to the surface. In the case of a lander, retrorockets would be needed for the controlled descent. For a penetrator, rockets would be needed only to de-orbit the craft.
3. Landing: Safe landing in terms of hazard avoidance, terrain slope, and cutoff of rockets after touchdown etc. For a penetrator, instrument survivability in the presence of high g loads.
4. Power: the use of RTGs or even RHUs could have significant implications for the launch approval process. Batteries could power systems over timescale of tens of days.
5. Environment: Instrumentation and electronics must survive the high radiation and low temperatures.

Mission Implications

The mass of any lander would be part of the science payload and in this aspect would compete with other science instruments. The planetary protection issues associated with any package that lands on the surface of Europa will certainly pose constraints on the overall mission in terms of isolation of the surface package before deployment, interfaces with the orbiter, and the deployment mechanism. The data from the lander would have to be relayed through the obiter.

2. Astrobiology Lander

Science

The highest priority science objective for astrobiology is the detection of signs of life. If Europa has an ocean, and if that ocean contains life, and if water from the ocean is carried up to the surface, then signs of life may be contained in organic material on the surface. Organics that derive from biological processes (dead organisms) are distinct from organics derived from non-biological processes in several aspects. First, biology is selective and specific in its use of molecules. For example, Earth life uses 20 left-handed amino acids. Second, biology can leave characteristic isotopic patterns. Third, biology often produces large complex molecules in high concentrations--for example chlorophyll. Evidence of life in an ocean may be found on the surface of Europa if there are regions of the surface containing relatively recent material carried up from the ocean. Direct sampling of Europan material is probably required since the detailed analysis required to detect biological characteristics is not likely to be possible via remote sensing. Organic material that has been on the surface of Europa for long periods of time would be reprocessed by the strong radiation field--probably erasing any signature of biological origin. A landed package containing a GCMS or equivalent instrument capable of obtaining a surface sample could do the desired analysis.

Technology Readiness of an Astrobiology Lander
An Astrobiology Lander has all the 5 technology issues listed above that are associated with a Geophysics Lander plus at least two more. These additional ones are

6. The need to have a sample acquisition system.
7. The need to target and land in region where there are young materials on the surface or the need to bore to pristine material below 1 m depth.

In contrast to the Geophysics Lander it is thought that the instrumentation and sample acquisition system needed to achieve the astrobiology science objectives are not consistent with penetrators due to volume and acceleration issues.

Mission Implications

The mission implications for an Astrobiology Lander are the same as those listed for a Geophysics Lander plus the added requirement to do site selection based on remote sensing before the deployment of the lander in order to find a site with young material on the surface. In addition, the operations of an Astrobiology Lander with sample acquisition and analysis will require a more complex interaction with the orbiter during the lifetime of the lander than a Geophysics Lander.

3. Astrobiology Dumb Impactor

Science

The search for signs of life in the organic material on the surface of Europa will likely require direct analysis of surface material. This could be accomplished with an Astrobiology Lander as discussed above or by the analysis on the orbiter of material ejected from the surface of Europa by either natural or artificial means. This latter approach leads to the suggestion of a dumb impactor (eg. a 10 kg copper ball) that hits the surface of Europa knocking material out in a plume that can then be sampled by the orbiter or a subspacecraft released from the orbiter for this purpose. In addition to ejecting samples for astrobiological analysis, a dumb impactor would contribute to the geophysical characterization of the surface materials if the impact and the plume could be analyzed.

Technology Readiness

An Astrobiology Dumb Lander has the same planetary protection and delta-V issues listed above that are associated with a Geophysics Lander plus at least three more. These additional ones are

3. Sample collection on the orbiter or any subsatellite. There are no good examples of collection in the expected velocity range for on-board analysis.

4. The need to target and land in region where there are young materials on the surface or the need to dig to a pristine material below 1 m depth.
5. The need to characterize the plume to allow for successful sampling. This would probably require at least two impactors, one would be a test impactor

Mission Implications

A dumb impactor payload has severe implications for the JIMO orbiter due to

1. Site selection as for the Astrobiology Lander requiring target selection based on a remote sensing survey.
2. Requirement to deploy a test impactor and observe the plume generated
3. Based on the test impact, deploy the second impactor and fly through the plume at the correct time and altitude (probably <10 km) on the same orbital pass (the plume is expected to last only ~1/2 hr).

4. Subsatellites for EM Fields, Plasma, and Gravity

Science

There are several high priority science objectives related to the measurement of EM fields, plasmas, and gravity that cannot be effectively done from the orbiter if the orbit perturbations are too frequent or the spacecraft electrical currents or fields are too high (eg., when the engines are running). Discussion at the workshop indicated that it would probably be the case that for most of the time while JIMO was in orbit about a moon the engines would in fact be off. This would obviate the need for a substatellite to make these measurements. Confirmation of this is one of the action items listed below.

NB: It was not clear at the workshop that the possible interference of the internal oscillations of the large JIMO orbiter structure (even with engines off) would interfere with gravity measurements. This needs further consideration.

Other mission implications are that multiple subsatellites would be needed (one for each icy satellite), RTGs are probably required to provide power over several months, planetary protection issues, and provision of a communications link for gravity tracking and telemetry.

5. Jupiter Probe

Science

Direct measurement of the deep thermal and wind structure and the elemental composition, in particular oxygen abundance, of Jupiter are required to address fundamental science questions that relate to the formation of the Jovian system – including the icy moons, to the formation of the Solar System as a whole, and the nature of other giant planets now discovered in other stellar systems.

Technology Readiness

Unlike the other auxiliary payloads discussed here, the Jupiter Probe can be based on a previously flown probe, the Galileo Probe. Thus technology readiness can be discussed in comparison to the Galileo Probe heritage. There are four areas of relevance.

1. The thermal protection system used for Jupiter entry from Galileo may be available. If not this would require a significant development and re-certification effort.
2. The need to reach deep pressures (100 bars) would require a pressure vessel kept cool, probably via phase-change material.
3. The deeper penetration raises telecom issues.
4. There may be technology development that could reduce the mass of a GCMS, the primary science instrument.

Mission Implications

The Galileo Probe was over 300 kg. Team X designs for a new Jupiter probe currently are about 200 kg. This mass is a significant fraction of the science mass payload for JIMO.

Although solutions appear to exist, further study related to telecom and trajectories appears required to determine how a Jupiter Probe could communicate with the JIMO orbiter.

Programmatic Aspects

At the workshop the question arose how to relate a possible Jupiter Probe on JIMO with the current call in the New Frontiers Program for a Jupiter Probe mission. Here is one possible way to approach this issue:

The strong science case for a Jupiter entry probe is well established (SSE Decadal Survey; JIMO Science Forum, Houston). Because of the first order science return from a deep penetrating Jupiter probe, it is recommended that NASA determine the most cost effective approach to accomplishing the probe measurements. At this time there appear to be two distinct choices for delivering a probe to Jupiter. The first approach is to consider a Jupiter mission proposed to the New Frontiers Program, which might include a Jupiter entry probe. The second approach is to consider a Jupiter entry probe as part of the JIMO mission payload. In each case, the entry probe should be competed in the same sense as any potential science instrument. Therefore, just as any science instrument might be proposed for either a New Frontiers mission or JIMO, the Jupiter probe could be proposed for either as well. The JIMO SDT could recommend that NASA entertain consideration of probes on both New Frontiers missions and JIMO, and when payload selections for either mission are made, the value and mission impact of any proposed Jupiter probe can be judged against any other proposed science instrument complement for that particular mission. This is an equitable procedure, since all science recommendations, including those regarding Jupiter entry probes for either the New Frontiers program or JIMO, are publicly available, either in the New Frontiers AO or the JIMO Science Forum recommendations publicly available on the web.

6. Recommendations and action items:

We have seven recommendations. We suggest that 3 (1-3) should be briefly reviewed at the September SDT meeting. 4 and 5 should begin after the SDT recommends including the auxiliary payloads. 6 and 7 are tasks for the SDT. Chris McKay has agreed to lead a response to 7.

1. Assessment of the JIMO spacecraft to meet fields and particles measurements. We recognize that this will be an ongoing process. Nonetheless we ask for a quick look at the assumption that the engines will be off during most of the orbital phases and that currents and fields can be kept to acceptable levels. If this proves to be impossible or impractical then this would require re-assessing the need for subsatellites.
2. Review of the project baseline approach for low temperature and high radiation survival.
3. Project approach to RHUs and/or RTGs. Will RHUs be on the spacecraft for engineering thermal management?
4. Telecom for auxiliary payloads
5. Accommodation of the auxiliary payloads in the spacecraft.
6. Studies of instruments available for use in high-g penetrators
7. Numerical analysis of plume dynamics for a dumb impactor.

APPENDIX 3: ICY SATELLITE ATMOSPHERE CHARACTERISTICS

This appendix summarizes our knowledge of the atmosphere of each of the icy Galilean satellites from the point of view of possible drag effects on an orbiting spacecraft. Therefore it focuses on the dominant atmospheric species, and touches briefly on minor species. It is not intended to guide the development of scientific investigations of these atmospheres. Those wishing a more detailed description of the atmospheres of the Galilean satellites should consult the recent comprehensive review by McGrath *et al.* (in press), from which much of the material in this appendix is derived.

Our understanding of the atmospheres of all the Galilean satellites (Table 1) is rudimentary in many respects. Here we draw attention only to those gaps in understanding that relate to the main topic. Important examples include known or suspected variations of atmospheric pressure over time or over the surface of the satellite. In general, the satellite atmospheres are not thoroughly sampled in either of these parameter spaces, so caution is prudent. The model atmospheres shown in the figures are not definitive, because, in addition to the caveats already mentioned, neither the average surface abundances nor the vertical temperature profiles are well constrained by observations.

Europa

The presence of a predominantly O_2 atmosphere on Europa has been inferred from HST observations of O emissions at 130.4 and 135.6 nm. The measured ratio of the intensities of the two lines implies that the emissions arise from excitation of O_2 by electron impact. The inferred O_2 abundance therefore depends on the flux and energy distribution of the electron population that excites the emissions. The O emissions have been detected on both the leading and trailing hemispheres of Europa. However, their spatial distribution is more complex than expected on the basis of existing models of plasma interactions with an optically thin atmosphere. This suggests the possibility of variations in pressure over the surface. An ionosphere is present, at least under some conditions. The dominant source appears to be electron impact ionization rather than photoionization. Except for the spatial variations in O emissions already mentioned, there is a general consistency between the pictures of plasma interactions, ionosphere, and optical emissions.

Ganymede

Our understanding of Ganymede's predominantly O_2 atmosphere comes from observations and analyses similar to those for Europa. Localized enhancements in O emissions in the polar regions are understood to arise from electrons trapped in Ganymede's magnetic field and accelerated into the atmosphere, in a process analogous to excitation of Earth's aurora. Thus the brightness variations are probably related to excitation, rather than variations in atmospheric abundance.

Callisto

Callisto's is the least known of the Galilean satellite atmospheres. Galileo NIMS detected emissions in a CO_2 band at 4.26 μm at altitudes to 100 km above the limb. From these observations were inferred the characteristics of the CO_2 atmosphere shown in the table. This is the only direct detection of Callisto's neutral atmosphere. However, Galileo radio occultation measurements showing the signature of an ionosphere have been interpreted in terms of a more abundant component consisting of O_2. The table also describes this component of the atmosphere, and the O_2 component is the basis for the model atmosphere in Figure 3.

Modeling

Figures A3-1-3 show model atmospheres for the three icy satellites. These were constructed using the values in Table 1. The models are based on a temperature profile having the lower 100 km (*i.e.*, ~3 scale heights) near the surface temperature, and the remainder at the thermospheric temperature given in Table 1. Above 100 km, the abundance is calculated using $n(r) = n_0 (R/r)2 \exp[-(r-R)/H]$, where R is the radius of the base, n_0 is the density at R, and H is the scale height (after Hall *et al.*, 1998). For the range of parameters in this work, the abundances computed in this way differ by less than a factor of 2 from those calculated using the formulation given by Chamberlain (*Theory of Planetary Atmospheres*, 1963):
$n(r) = n(R) \exp[-(\lambda(R) - \lambda(r))]$, where $\lambda(r) = r/H(r)$.

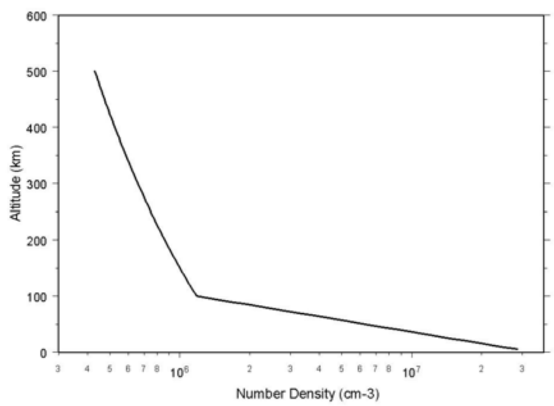

Figure A3-1. Number density vs. altitude for Europa's O_2 atmosphere.

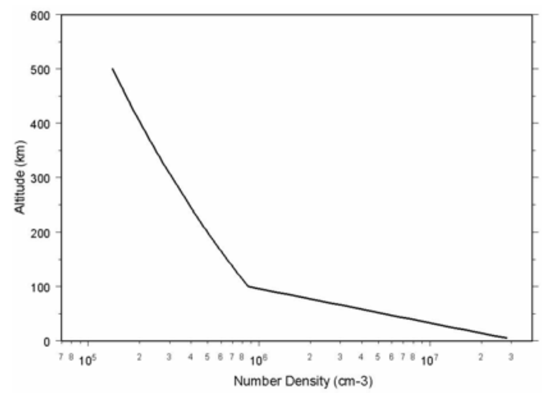

Figure A3-2. Number density vs. altitude for Ganymede's O_2 atmosphere.

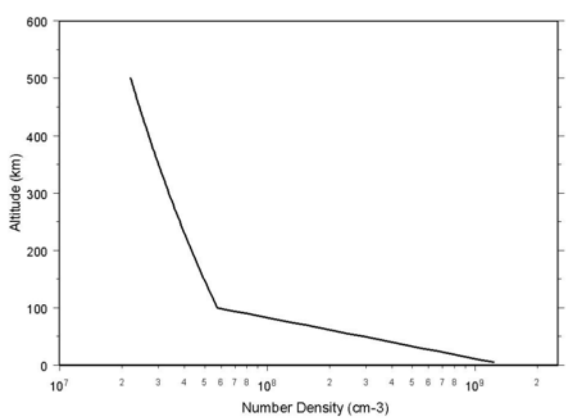

Figure A3-3. Number density vs. altitude for Callisto's O_2 atmosphere.

References

Hall, D. T., Feldman, P. D., McGrath, M. A., and Strobel, D. F.,The far-ultraviolet airglow of Europa and Ganymede, *Ap. J.* 499, 475, 1998.

McGrath, Melissa A., Emmanuel Lellouch, Darrell F. Strobel, Paul D. Feldman, and Robert E. Johnson, Satellite Atmospheres, in *Jupiter: Planets, Satellites, Magnetosphere*, Ed. F. Bagenal, T. Dowling, W. McKinnon, Cambridge University Press. (in press).

APPENDIX 4: JIMO SPACE SYSTEM

The notional JIMO space system is illustrated in Figure A4-1. The JIMO space system is composed of three basic modules: the reactor module, consisting of the reactor, its radiation shield, a re-entry shield, and the reactor instrumentation and control; the space system module, consisting of the space system bus, reactor power conversion and heat transfer segment, electric propulsion, and the launch vehicle adapter; and the mission module, consisting of all mission-unique subsystems, including the science instruments, their support structures, and any auxiliary payload.

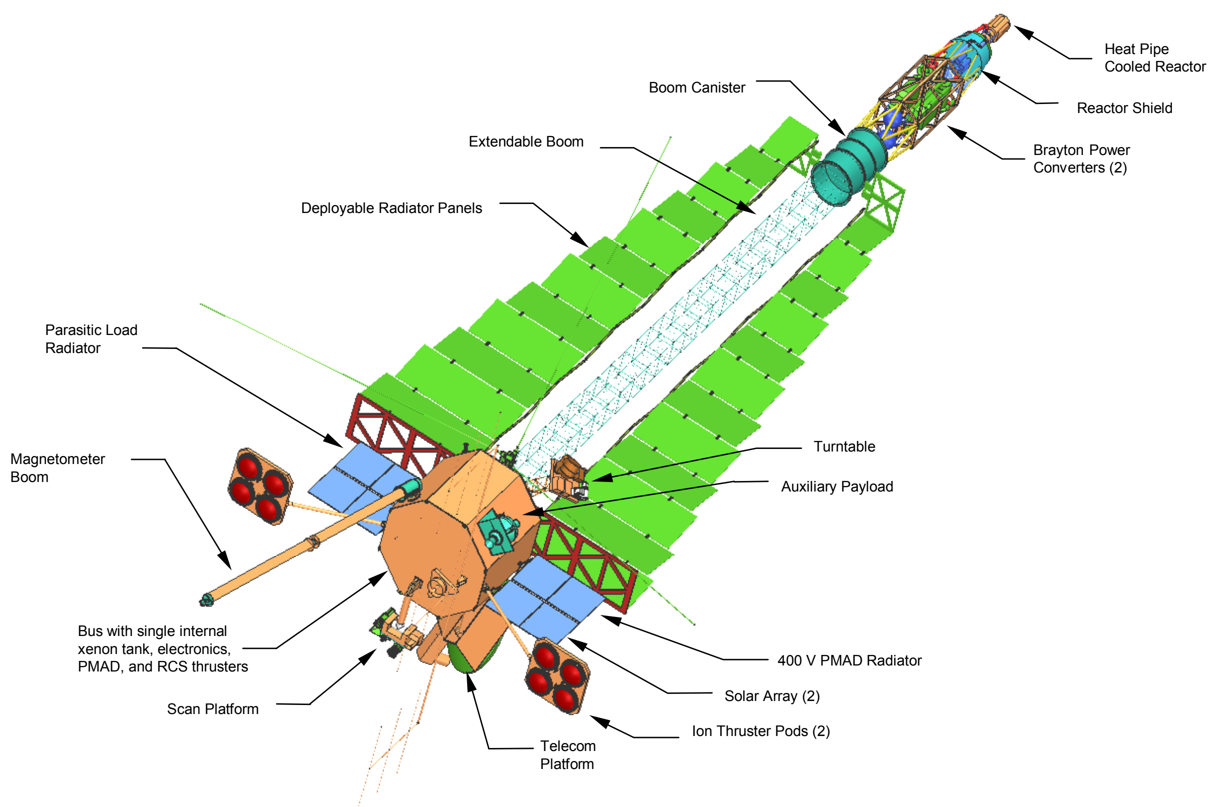

Figure A4.1. Notional Heat Pipe-Brayton JIMO Space System.

The expected radiation dose from the Jovian environment and from the reactor at the location of the mission module (inside the radiation shield cone) for the TB1 baseline is predicted to be 6 Mrad total ionizing dose from gamma rays plus a displacement damage dose of 8.6E12 equivalent 1-MeV neutons/cm^2 behind shielding of 100 mils of aluminum.

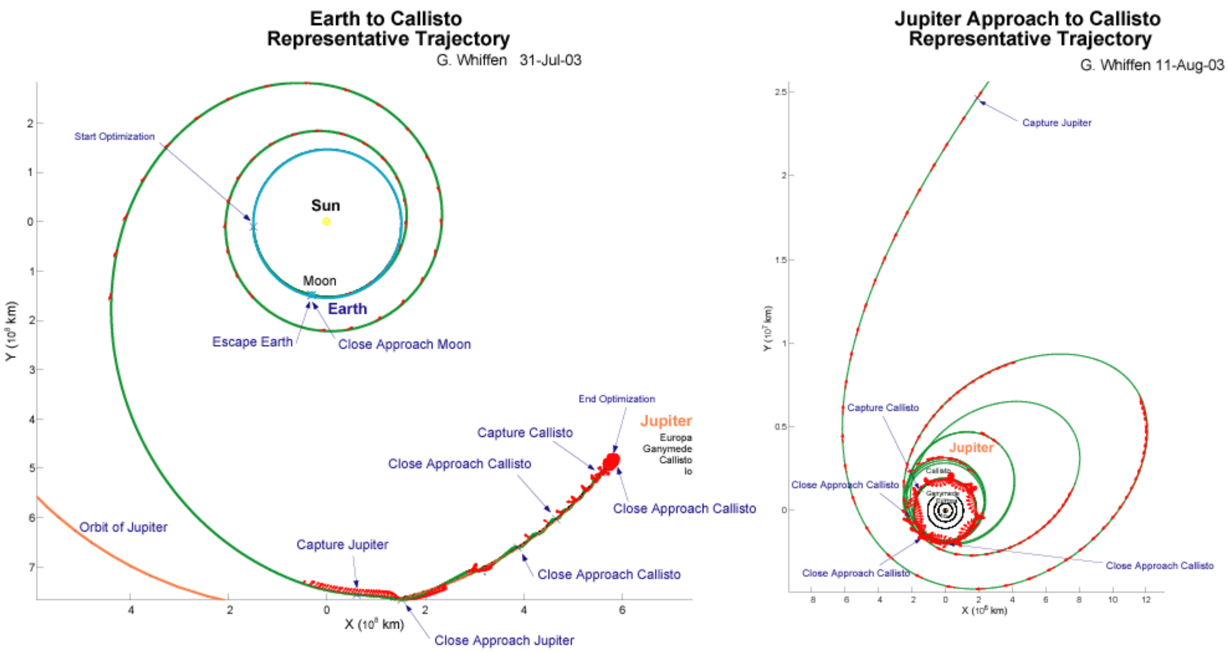

Figure A4.2. Representative JIMO trajectory from Earth to Jupiter.

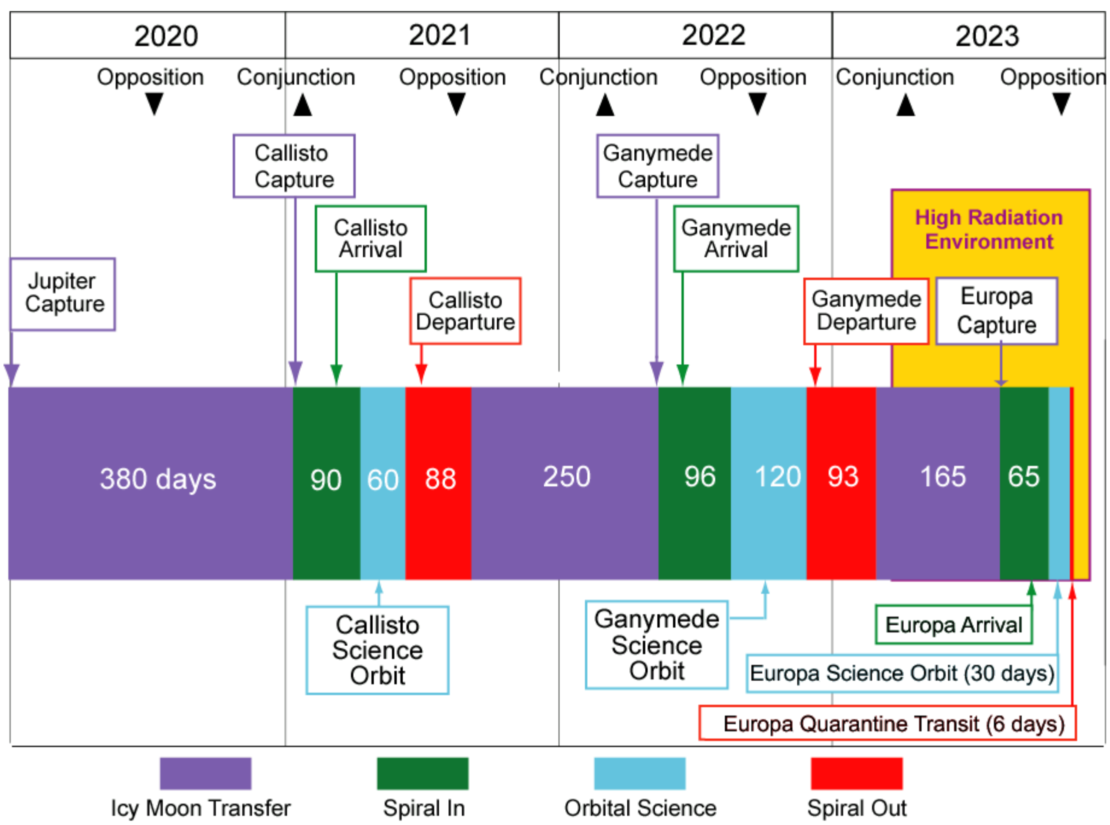

Figure A4.3. Typical timeline while in the Jovian system.

Figure A4-4 plots the nodal regression rate for circular Europa orbits vs. inclination for different orbital altitudes. For comparison, at an altitude of 100 km and inclination of 70°, Ganymede's nodal rate is -0.41°/day, while for Callisto it is -0.09°/day.

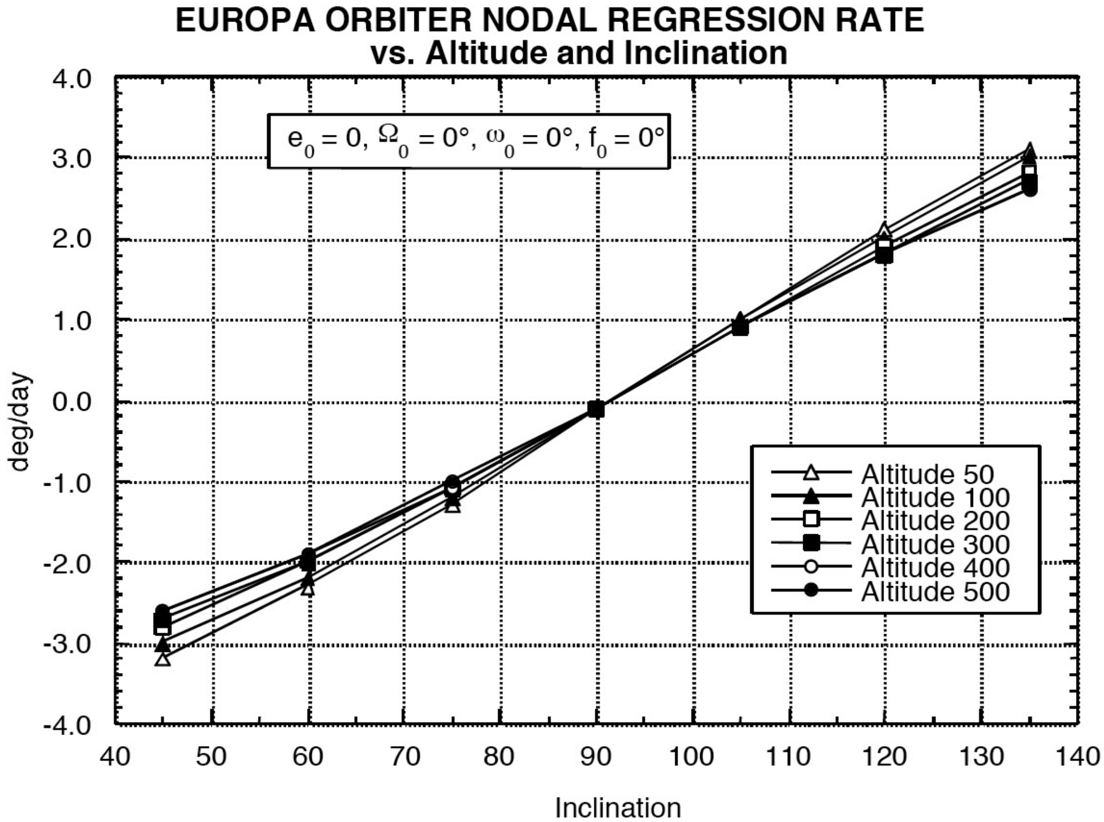

Figure A4.4. Nodal regression rate of circular Europa orbit.

APPENDIX 5: LIST OF ACRONYMS

AO	Announcement of Opportunity
DAWG	Data Archiving Working Group
DSN	Deep Space Network
EDR	Experiment Data Record
EM	Electromagnetic
ESSP	Europa Surface Science Package
FWHM	Full Width Half Maximum
IR	Infrared
NIR	Near Infrared
JIMO	Jupiter Icy Moons Orbiter
JPL	Jet Propulsion Laboratory
LPI	Lunar and Planetary Institute
NASA	National Aeronautics and Space Administration
NEP	Nuclear Electric Propulsion
NRC	National Research Council
PAE	Payload Accommodation Envelope
PDS	Planetary Data System
PSG	Project Science Group
SAR	Synthetic Aperture Radar
SDT	Science Definition Team
SOC	Science Operations Center
RTG	Radioisotope Thermoelectric Generator
RHU	Radiogenic Heatsource Unit
TB1	Technical Baseline 1
UV	Ultraviolet